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Best practices and methodological guidelines for conducting gas risk assessments

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Introduction

The EC Regulation concerning measures to safeguard security of gas supply (EC/994/2010) requires member states to make a full assessment of the risks affecting the security of gas supply. According to Article 9, this risk assessment must:

- (a) use the infrastructure and supply standards (articles 6 and 8);
- (b) take into account all relevant national and regional circumstances;
- (c) run various disruption scenarios;
- (d) identify the interaction and correlation of risks with other Member States.
- (e) take into account the maximal interconnection capacity of each border entry and exit point.

The objective of this report is to provide guidance and advice for performing risk assessments. It will do so by first providing a literature review, and then by proposing a basic structure for undertaking a gas security risk assessment, in accordance with best practices and standard procedures found in risk management.

1 A review and categorisation of selected literature

1.1 Scope and Objectives

The first step in assessing the complex and disparate literature on (national or regional) risks to security of supply (and associated threats, hazards, vulnerabilities, and so on) is to identify the boundaries within which a given analysis falls. In doing so, it is also useful to recognise the different objectives of each study and the primary concepts employed.

At the outset it is necessary to note that the literature reviewed are not all classical risk assessments. In fact, public documents that provide concrete examples of risk identification, analysis and evaluation are relatively rare. As a proxy for assessing such literature, which can often be kept confidential by operators, we will strive to review literature relevant to risk, including energy security.

1.1.1 International Standards

At the most **general** level are international institutions striving to provide a generic standard risk assessment methodology applicable to any system. Here the International Standards Organisation (ISO) and the International Risk Governance Council (IRGC) are instructive examples of institutions that provide a generic methodology with which to identify, analyse and evaluate risk.¹ These standardised approaches provide a first approximation of how to approach risk and the steps by which a risk assessment can be conducted, regardless of the nature of the organization or the risks it is facing. For example, the ISO 31000 document entitled 'Risk Management' provides principles and generic guidelines on risk management, of which the process of risk assessment forms one part. Similarly, the IRGC released a 'white paper' on risk governance that provided an integrative approach whereby risk assessments formed part of the 'risk appraisal' process, which in turn required a judgement about risk acceptability. Several other such general approaches exist that can provide a basis for considering best practices.²

1.1.2 European projects on gas/energy security

¹ International Standards Organisation (ISO) 31000: 2009 at http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=43170; International Risk Governance Council (IRGC), White Paper on Risk Governance; towards an integrative approach, 2005 at http://www.irgc.org/IMG/pdf/IRGC_WP_No_1_Risk_Governance_reprinted_version.pdf

² See the results of the 'desktop study' of general RA approaches in EURACOM Deliverable 2.1; there are also related international approaches, such as those on asset management (e.g. PAS 55 published by the British Standards Institutions) that overlap with the scope of risk assessment approaches.

Moving away from general approaches to specific studies regarding the energy/gas markets, there is an identifiable body of literature on risk that analyses the **energy system** as a whole. Here the literature can be sub-divided between studies that are confined to one country or those that strive to analyse regional or international risks (with a particular emphasis on cross-border interdependencies between systems and networks). Situated in the latter category, a group of 7th Framework Programme projects (EURACOM, REACCESS, SECURE, as well as COUNTERACT and INTEGRISK³) endeavoured to analyse risks pertaining to the entire European Union, singling out in particular critical infrastructures (including entire energy networks).

The target of analysis in the EURACOM project, for example, was to identify a common and holistic approach for risk assessment (and contingency planning) in the whole energy sector. This project drew extensively on the EURAM method – European Union Risk Assessment Method – a basic common methodology for the analysis of interdependencies between Critical Infrastructures (CI) of the same sectors and between CI of different sectors and different countries. In applying a risk assessment method to the gas system, Euracom narrowed the scope of analysis to transmission, which was justified “by the fact that energy grids are the pivotal point of dependencies and cascading effects at European scale whether we talk about dependencies between grids themselves or their interaction with source and distribution.”⁴

The objective of the REACCESS project was to evaluate the technical, economical and environmental features of present and future energy corridors, within Europe and between Europe and the energy supplying regions of the world. This evaluation has been carried out through a detailed representation of the different typology of infrastructures, technologies and flows (thanks to a complex framework of three integrated energy system models).

Focusing on the study of the potential need of developing new infrastructures in the EU gas transmission network, and as a result of the obligations imposed by the European 3rd Energy Package, ENTSOG has developed two successive studies^{5,6}. Both studies adopt a scenario based approach that helps identifying EU regions that could not have enough capacity to achieve full supply demand balance under specific High Demand Conditions.

There are other projects, whose scope remains at the European level, which are useful as guideposts for determining energy-related risks. For example, the Energy Research Centre of the Netherlands took as their domain of analysis the EU and its member states’ energy supply

³ EURACOM : European Risk Assessment and Contingency Planning Methodologies for Interconnected energy Networks (<http://www.euracom-project.eu/>) ; REACCESS : Risk of Energy Availability: Common Corridors for European Supply Security (<http://reaccess.epu.ntua.gr/>) ; SECURE : Security of Energy Considering its Uncertainty, Risk and Economic implications (<http://www.secure-ec.eu/>); COUNTERACT: Consortium Of User Networks in Transport and Energy Relating to anti-Terrorist ACTivities; iNTeG-Risk - Early Recognition, Monitoring and Integrated Management of Emerging, New Technology-related Risks (<http://www.integrisk.eu-vri.eu/>)

⁴ EURACOM, Deliverable 2.3, pg. 30

⁵ European Network of Transmission System Operators for Gas (ENTSOG). ‘European Ten Year Network Development Plan 2010 - 2019’. 2009.
http://www.entsog.eu/download/investment/ENTSOG_TYNDR_B_23dec2009_.pdf

⁶ European Network of Transmission System Operators for Gas (ENTSOG). ‘Ten-Year Network Development Plan 2011 - 2020’. 2011.
http://www.gie.eu.com/adminmod/show.asp?wat=TYNDP_Report_110217_MQ.pdf

security.⁷ Similarly, the study analysing infrastructure projects, market integration and security of supply in Europe, initiated by the European Regulators' Group for Electricity and Gas (ERGEG), with the model-based analysis performed by the Institute of Energy Economics at the University of Cologne (EWI), provided a highly detailed description of EU gas networks in order to develop a European perspective on security of supply issues.⁸ A key objective of this study was the identification of existing and expected potential infrastructure bottlenecks. In another example, the World Energy Council applied vulnerability indicators to EU member states' energy systems in the event of supply crises.⁹

1.1.3 National Assessments of Gas Security

There is much useful literature whose scope centres on specific features of national energy (or gas) systems. This literature can be useful for setting out the context and tools of analysis for considering risk. The scope and objectives of such studies tend to overlap with the steps necessary to conduct a risk assessment. Indeed, these studies describe the institutional framework, market organisation, infrastructure, and energy flows that together constitute the national energy system. The UK is an instructive example whereby studies adopt different scope conditions in their analyses. For example, a consulting report commissioned by the UK government focussed on the security of UK gas supply between 2010 and 2025, to assess options for improvement (e.g. through storage and demand side response to protect consumers).¹⁰ The system was described with a high level of granularity, detailing the drivers and barriers for gas infrastructure, storage and distillate backup investment in particular. A similar report by a different consulting group focussed on the effectiveness of current gas security of supply arrangements in the UK, narrowing the scope to an assessment of the costs related to forced outages of gas and weighing them against the cost of new gas infrastructure investments (particularly in the industrial sector).¹¹ Finally, a study by UKERC explored ways of enhancing the 'resilience' of the UK energy system as a whole, to withstand external shocks and how such measures interacted with those designed to reduce carbon emissions.¹² In each of these studies, the domain of analysis was different yet all were concerned with the risks posed to the UK national energy system.

⁷ Energy Research Centre of the Netherlands (ECN), "EU standards for energy security of supply; updates on the Crisis Capability Index and the Supply/Demand Index" *ECN-CIEP Joint Report*, 07-004, April 2007 at <http://www.ecn.nl/docs/library/report/2007/e07004.pdf>

⁸ Institute of Energy Economics at the University of Cologne (EWI), *Model-based Analysis of Infrastructure Projects and Market Integration in Europe with Special Focus on Security of Supply Scenarios*, Study conducted for European Regulators Group for Electricity and Gas (ERGEG), May 2010

⁹ World Energy Council, *Europe's Vulnerability to Energy Crises*, 2008 at <http://www.worldenergy.org/documents/finalvulnerabilityofeurope2008.pdf>

¹⁰ Poyry Consulting GB, *Gas Security of Supply And Options for Improvement*, a report to Department of Energy and Climate Change, March 2010 at http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20markets/gas_markets/114-poyry-gb.pdf; Poyry Consulting GB, *Security Of Gas Supply: European Scenarios, Policy Drivers And Impact On GB*, A report to Department of Energy and Climate Change, June 2010b at http://www.decc.gov.uk/assets/decc/what%20we%20do/uk%20energy%20supply/energy%20markets/gas_markets/115-poyry-europe.pdf

¹¹ Oxera, *An assessment of the potential measures to improve gas security of supply*, 2007, at <http://www.oxera.com/main.aspx?id=6133>

¹² UK Energy Research Council (UKERC), *Building a Resilient UK Energy System*, March 2009, at www.ukerc.ac.uk/support/tiki-download_file.php?fileId=618

1.1.4 National Gas Risk Assessments

The studies of national security of supply are useful for determining the parameters to take into account when assessing risk. However, the studies above do not follow classical risk assessment methods. Their objectives, though varying, are different to the conventional process of risk identification, analysis and evaluation.

Studies that *explicitly* adopt a risk assessment methodology/approach to the gas sector are not generally publicly available. Four exceptions are the risk assessments provided by the three Baltic States (in close cooperation with DG-ENER) as well as an example from the United States, namely the comprehensive evaluation of Alaska's gas infrastructure conducted by two consulting firms.¹³ Such studies put into practice, either implicitly or explicitly, the theories and methods described in the general approaches to energy-related risks set out above, applying them to the exigencies of the natural gas sector.

The Alaskan report (ARA 2009) represents a classical safety-related assessment, with the scope of the analysis limited to natural hazards and the technical reliability of gas networks within the U.S. state. The scope of the risk assessments adopted by the Baltic States is broader, considering the whole gas system from the total energy security point of view. Indeed, Lithuania, Estonia and Latvia discuss in depth their respective energy balance, considering the supply and demand of all available and exploited fuels within their given territory. These reports tend to discuss regional interdependencies such as the shared reliance on Latvia's Inčukalna Underground Gas Storage (UGS), and the common dependence on a single external supplier – prompting a more regionally-focussed scope of assessment. But there are also national differences. The Lithuanian Risk Assessment, for example, applied a special focus on the applicable measures to safeguard the district heating (DH) sector, which was the largest user of gas: in this context, Lithuania's storage requirements, interruptible consumers, procedures on energy supply to consumers in case of extreme events, as well as demand projections up to 2020 all laid special emphasis on the DH sector.

In risk assessments pertinent to the gas sector, the scope of analysis can be further sub-divided into geographical domain (e.g. EU/regional/ national/sub-national), consideration of other systems (e.g. oil, coal, electricity or in fact the entire energy system), and the time horizon (e.g. short, medium or long-term assessments).

1.2 Key Concepts and Variables

This review can only provide a snapshot of the huge literature attempting to analyse risks related to energy – and in particular natural gas – security. In the context of a classical risk assessment following best practices, the key question that arises in surveying the relevant

¹³ Estonia, *Risk Assessment of Estonian Gas Supply*, 2010 ; Latvia, *Security of Supply Risk Assessment – Natural Gas*, 2010 ; Lithuania, *Risk assessment and simulation of potential scenarios in regard to interruptions of natural gas supply in Lithuania*, Ministry of Energy, April 2010, Alaska Risk Assessment (ARA), *Comprehensive Evaluation and Risk Assessment of Alaska's Oil and Gas Infrastructure; Proposed Risk Assessment Methodology*, Doyon Emerald and ABS Consulting March 2009 at http://www.dec.state.ak.us/spar/ipp/ara/documents/Proposed%20Risk%20Assessment%20Methodology_Rev%201.pdf

literature is what risks, vulnerabilities, threats and hazards are considered, and whether those identified are explored in terms of their causes as well as likelihoods and consequences.

Rather than identifying specific risks to a given system, **general** approaches to risk give an indication of the methods by which risks can be identified and categorised. According to IRGC and ISO, the general methods for identifying risk range from brainstorming and check-lists to more formal methods such as Hazard and Operability Analysis (HAZOP) and Failure modes and effects analysis (FMEA). The HAZOP process is a qualitative technique based on the use of guide-words which question how the design intention or operating conditions may not be achieved at each step of the design, process, procedure or system. FMEA is a technique used to identify the ways in which components, systems or processes can fail to fulfil their design intent. These are merely two examples of a broad range of methods used to identify risk – among others SWIFT – structured ‘what-if’ teams – Scenario analysis, Delphi, and so on.¹⁴

In the literature specific to the **energy system**, risks tend to fall into categories. Three FP7 Projects (REACCESS, SECURE, and EURACOM) attempted a relatively comprehensive mapping of the wide range of risks facing the (EU) energy system. In the case of REACCESS (Del. 4.5.1), factor analysis was applied to four identified ‘risk vectors’ (social, energy, political and economic), each of which was represented by several indicators (e.g. corruption, peace and conflict indicators were among those used for the ‘political’ vector). SECURE categorized risk according to technical, economic, regulatory, geopolitical and environmental sources (Del. 1.2). EURACOM promoted a holistic, all-hazards approach to identifying risk, compelling energy operators to consider them according to intentional, failure/accidental, natural and cascaded categories.

Risk identification will often depend on the scope of the study, but whatever the domain of analysis it is important to recognize the provenance of risks (e.g. whether they are exogenous or endogenous to the system). In approaches that observe risk in the **gas sector**, risks may be of a different nature to those identified for oil or coal. For example, given its dependency on a single gas supplier, the main risks identified by Lithuania are external factors - a) gas as political weapon; b) political/commercial disputes (as well as long-term supply contracts) and c) terrorism. Of course, this does not discount the document’s consideration of other risks, such as natural hazards or internal technical problems, which may be of relevance. A different approach was adopted by the Estonian Risk Assessment, which used Delphi expert judgement and fault tree analysis to differentiate external from internal risks (the latter including factors such as vandalism, natural disasters, and technical infrastructure faults – leaks, corrosion, etc).

Importantly, several approaches to classifying energy-related risks stress the importance of the time scale in which to consider these risks, since some are associated with shocks (e.g. sudden cuts in supply or hikes in price) and others with stresses (e.g. adequate long-term investment, geological depletion rates and so on).¹⁵

¹⁴ Dalkey, N.C., “An experimental study of group opinion”, RAND Corporation Report RM-5888-PR, 1969; see also ISO 31010 :2009, Annex A, p. 23-27 at

http://www.iso.org/iso/catalogue_detail?csnumber=51073

¹⁵ International Energy Agency (1995) *Natural Gas Security Study*. OECD/IEA, Paris, France at www.iea.org/textbase/nptoc/archive/Nat_Gas1995_TOC.pdf

The process and methods used to identify risk have an important effect on the remaining assessment. For example, the risk assessment conducted for the Alaskan gas sector analysed a comprehensive set of scenarios selected through a rigorous methodology, but the scope of the analysis was limited to natural hazards and the technical reliability of infrastructure (e.g. no market-based or geopolitical risks were considered).

1.3. Tools and Methods

The tools and methods used to analyse risk and related variables (security, vulnerability, exposure, resilience, and so on) are as numerous as they are multi-faceted. The gas system is characterized by a high degree of complexity (large interconnected infrastructures), uncertainty (wide and indeterminate causes and consequences of risk), and ambiguity (different meanings assigned to risk and its acceptability). Cause-effect relationships are difficult to discern and the high degree of variation in both causes and effects pose a problem for validation of risk assessments. In this case, analysis of risks will inevitably be probabilistic rather than deterministic.

The reviewed literature identified factors that affect consequences and likelihood in different ways. For probability estimation and assessment of consequences either quantitative or qualitative methods were used. Oxera 2007 and ARA 2009 used quantitative methods for probability estimation, whereas the Baltic RAs applied qualitative methods. With respect to consequence assessment some studies used indicators/standards including N-1, others used formal models (e.g. EWI 2010, Poyry 2010, ARA 2009 and both REACCESS and SECURE).

1.3.1 Indicators/Standards

Many studies of energy security make use of **indicators**. Some are relatively simple expressions of data. For example, 'gas import dependence' is commonly expressed as total gas imports divided by total inland gas consumption.¹⁶ Other calculations are somewhat more complex, taking the form of an index. For example, the N-1 formula is expressed using a number of separate indicators which together describes the ability of a country to satisfy total gas demand in the event of disruption of the single largest gas infrastructure.¹⁷ This indicator, besides forming a standard within the framework of EC Regulation 994/2010, has been employed by the Baltic State Risk Assessments.

Another useful index borrowed from economics is the *Herfindahl-Hirschman Index* (HHI), which provides a measure of market concentration. In the energy sector, this index has been used to determine a country's level of supply diversification (by calculating the sum of the squared market shares of each supplier for a given country). A similar measure found in biology, the *Shannon–Wiener index*, has also been used to determine diversity not only in imports but also in relation to the level of fuel mix diversification.¹⁸

¹⁶ other simple indicators are reserves-to-production ratio (proven reserves / primary production) and energy intensity (TPES/GDP), see annex 2

¹⁷ See the annex of Regulation 994/2010. In this context, the n-1 principle refers only to gas, and therefore does not take into account substitution with other fuels.

¹⁸ ECN, *Designing indicators of long-term energy supply security*, ECN-C--04-007, January 2004 at www.ecn.nl/docs/library/report/2004/c04007.pdf

Other indices have been created specifically for the energy sector. Gnansounou and the World Energy Council have put forward an *Energy Vulnerability Index*, which is derived from the root mean square of five indicators (namely energy intensity, oil and gas dependency, electricity supply vulnerability, CO₂ emission, and non-diversity in transport fuels).¹⁹ The Energy Research Centre (ECN 2007) in the Netherlands has postulated a *Crisis Capability Index* (CCI) as part of its broader attempt to provide an energy supply security standard for the EU. The CCI compares the values from a checklist assessing risks with a similar checklist for mitigation strategies, giving an overall indication of a country's exposure to risk. ECN's goal was to aggregate this and a Supply/Demand Index in order to arrive at a single *energy security index*. A somewhat similar approach has been adopted by the International Energy Agency (IEA) in Energy security and climate change²⁰, followed by the report "Analysis of impacts of climate change policies on energy security", developed by Ecofys for the EU.²¹ The most recent example of this approach is the IEA's MOSES indicator, which restricts its scope conditions to short-term energy security and explicitly denies consideration of long-term factors "such as the environmental impact of different energy sources and systems, rapid growth in demand, and depletion of natural resources. With our focus on physical disruptions, MOSES also excludes economic issues related to affordability and volatility of energy prices."²²

Other institutes developed more expansive indicators. For example, the U.S. Chamber of Commerce sponsored a study that used 37 metrics spread across 9 categories comprising 4 sub-indexes that together constituted one index of U.S. energy security risk.²³ The FP7 Project REACCESS used statistical methods such as regression and factor analysis to quantify a number of 'risk vectors' (social, political, energetic, and economic) that together resulted in a single index, to be used in the model based scenario analysis which was the core of the project.²⁴

Indicators form the backbone of a gas supply risk assessment. They are useful to establish the context/parameters of the system, in some cases they can also provide an indication of the vulnerabilities in the system. However, by themselves they are insufficient for performing a risk assessment, as they say nothing about an acceptable level of risk. Rather, their main purpose is to indicate to policy-makers the current state of the system by measuring inputs that can be considered a proxy for the potential risk and/or magnitude of an energy security impact, should it actually occur. Indeed, even the most sophisticated sets of indicators do not measure the vulnerability of the energy system, nor its resilience: they are instead measures of variables which are only "proxy" of the vulnerability of the system (Ecofys 2009). Still, in some cases they

¹⁹ Gnansounou, E., "Assessing the energy vulnerability: Case of industrialised countries," *Energy Policy* 36, 2008, 3734–3744 at <http://www.sciencedirect.com/science/article/pii/S0301421508003510>

²⁰ International Energy Agency (IEA), *Energy Security and Climate Policy*, 2007
http://www.iea.org/publications/free_new_Desc.asp?PUBS_ID=1883

²¹ ECOFYS, Analysis of impacts of climate change policies on energy security, November 2009 at http://www.ecofys.nl/com/publications/brochures/newsletters/analysis_impacts_climate_change.htm

²² IEA, *Energy Security Indicators*, IEA/GB(2011)23, May 2011

²³ Institute for 21st Century Energy, *Index of U.S. Energy Security Risk; assessing America's vulnerabilities in a global energy market*, U.S. Chamber of Commerce, 2010 at www.energyxxi.org/energysecurity/; in 2009 the US Energy Security Risk was 83.7 (with its highest level of 100 reached in 1980 and its lowest of 72.6 in 1994.).

²⁴ Here, the authors produced an energy risk scoring table using a sample of 158 countries (Norway scoring first, Afghanistan scoring last, and Mexico scoring 31st). See REACCESS Deliverable 4.5.1

are used as benchmarks or standards with which to gain a clearer idea of the vulnerability/exposure of the gas system to risk.

1.3.2 Model based scenario analysis

In addition to the use of indicators, studies of energy security have also employed **scenario analysis** and **models** to analyse risks to the gas/energy system. There are a wide range of models developed that can be applied to the gas system. The annex provides a detailed list of models and their major characteristics.²⁵

Several different models can be adopted: energy system models (REACCESS, SECURE, UKERC 2010) aim to represent all the interactions between all the components of the wide energy system; partial equilibrium economic models of the gas market (Pöry 2010, EWI 2010) are not able to represent these interactions, but are more detailed with respect to some characteristics of the gas markets.

Pöry (2010a,b) adopted Pegasus ('Pan-European GAS + US') to project gas prices and flows and examine the interaction of supply and demand worldwide (17 European zones + US and Japan) on a daily basis, to estimate weekday/weekend differences, flows of interconnectors and gas flows in and out of storage in detail. Interconnection from GB to the Continent were modelled by minimising the cost of supplying gas to both zones, subject to both the capacity and the cost of transiting gas across the interconnectors. The major storage types were modelled accurately for each zone, each with its own injection and withdrawal rates, total storage capacity and cost of injection/withdrawal. The worldwide LNG market was modelled by considering all existing, under construction, proposed and conceptual LNG liquefaction projects worldwide, as well as LNG re-gasification terminals. Pegasus assumes perfect foresight, implying that alternative supplies are available when required.

The TYNDP developed by ENTSOG aimed to assess the resilience of the European gas network through scenario development and subsequent modelling of the integrated network based on those scenarios. The network model is based on a simple top-down approach, using countries as basic building blocks interlinked by cross-border capacity (TYNDP 2011-2020).

Studies that make use of models and scenarios often go beyond an assessment of the pure physical impact of energy supply disruptions, to find the level of risk which is "acceptable" for the specific system under analysis, so as to strengthen security of supply at the lowest cost. Often studies will assess the economic/commercial impact of supply shocks or even long-term stresses. For example, Pöry Consulting (2010 a/b) first estimate the probabilities of unserved energy in a wide number of situations, then estimate the "economic impact" of a loss of load by using as a proxy for the effect of unserved energy the impact to GVA (gross value added) of the above unserved energy volumes; by multiplying this cost through the probability of each scenario, they eventually convert this to an "expected annual average cost". Similarly, UKERC (2010) starts from a range of scenarios with different degree of resilience to simulate possible shocks to the UK energy system that impact on gas supply facilities; they estimate the impact of these shocks in terms of energy unserved (mcm), value of energy unserved (£m) and change in

²⁵ SECURE used "Poles", UKERC 2010 used "Markal-Med", "WASP", "CGEN"; JRC uses "GemFLOW", "SynerGEE"; Pöry uses "Pegasus".

system operating costs (£m); as a last step, they assess how system costs and welfare costs change in moving from the Reference and Low-Carbon scenarios to the Resilient and Low-Carbon Resilient scenarios respectively. Finally, the Netherlands Bureau for Economic Policy Analysis (CPB - 2006) assessed the costs and benefits of a set of possible security of supply measures against a baseline “disturbance-free” scenario; the benefits in particular were measured through the costs incurred by a disruption: partial-equilibrium energy market models were used to assess direct effects of disturbances within energy supply on energy demand and prices, while the indirect, macroeconomic consequences are analysed using Athena, a dynamic multisector model for the Dutch economy.²⁶

1.4 Results and Outcomes

Outputs from the risk assessments of the natural gas sector commonly provide risk matrices (see section 3.2.3.1). For example, all three Baltic state RAs presented the acceptability of the various risks posed to their respective gas systems using 3x3 or 4x4 risk matrices. Similarly, ARA 2009 provided a 5x3 risk matrix for reliability consequences, presenting it as loss of revenue to the State due to production losses. In addition, this report drew on risk histograms and summaries, the latter showing percentages of safety and reliability risk based on characteristics of identified scenarios.

In addition to these classical risk evaluation tools, some reports present an assessment of alternative possible energy security strategies, albeit using different variables and providing different outputs in relation to their scope. Basically, their aim was to compare the economic impact of supply interruptions with the benefits of possible security measures. For example, Oxera’s cost-benefit analysis was an assessment of the alternative measures to increase security, based on their cost of implementation and the expected costs of forced outages (calculated as sum of probability of interruption times cost). Alternatively, Poyry’s analysis assessed a list of possible options, by estimating the reduced cost of expected demand loss (and its net present value) produced by the implementation of these measures, as well as the implementation and investment costs of these measures. The Dutch CPB report presented a cost-benefit analysis of two policy options, computing break even frequencies to assess the expected efficiency of these options.

1.5 Conclusion of the literature review

This review has demonstrated that a great deal of variety exists in the recent literature assessing security of gas supply, at national or regional level. Most of the reports reviewed in practice do not follow internationally-recognised approaches such as those found in ISO or IRGC. In fact, they do not explicitly call themselves risk assessment, and are therefore not concerned with a rigorous methodology for assessing risk. Often they have a narrow purpose, such as assessing the current state of the energy system (but not assigning likelihoods or probabilities to possible contingencies) or evaluating the potential for enhancing energy security (by undertaking cost-benefit analysis).

²⁶ Netherlands Bureau for Economic Policy Analysis (CPB), *Energy policies and risks on energy markets; a cost-benefit analysis*, Centraal Planbureau, 2006 at <http://www.cpb.nl/node/10223>

Nonetheless, the literature reviewed, even if often far from a standard RA methodology, can still be very useful. As a matter of fact, in many cases single components of most of the reviewed studies are closely related to a risk assessment methodology, sometimes employing some of the same tools and methods. They can therefore be used as good practices that can be replicated to carry out the specific steps of a proper RA.

The eclectic nature of the literature reviewed is a natural product of the ambiguity surrounding the concept of 'risk' and 'energy security.'²⁷ But this is not just a semantic squabble: the definition of the system/parameters and the identification of risks that are to be analyzed affect not only the outcome of the Risk Assessment but also the risk mitigation strategies (in the case of Regulation 994/2010 – the emergency/preventive plans).

The main lesson to draw from this literature review is that it is very important to have a methodology that clearly identifies the system under consideration, the specific risks affecting this system, and the criteria for assessing them (e.g. measure of damage, likelihood/consequences). Therefore, regardless of the variety of approaches, the main, essential components of any risk assessment that cannot be ignored is **a) establishing scope/context, b) identifying risks, c) identifying probabilities/likelihoods, d) assessing consequences/impacts, e) and evaluating risks.**

²⁷ for a discussion of the problems in defining energy security, see Chester, L, "Conceptualising energy security and making explicit its polysemic nature," *Energy Policy*, Vol. 38, 2010, pp. 887-895. For an academic discussion of the concept of risk see Aven, T, "Misconceptions of Risk", Wiley, 2010

2 Objectives of the Practical Guidelines for the Risk Assessment

Regulation 994/2010 requires member states to carry out a Risk Assessment, but it does not provide a specific methodology for performing it. Still, in order to be able to formulate a coherent picture about the risks related to security of gas supply on a regional and on a European level, the outputs of the national assessments need to be consistent and comparable with each other and should be based on similar criteria for examining threats and hazards.

Here, an “inverse decision-based” approach is proposed to select the methodology to be adopted. In other words, the Risk Assessment methodology can only be identified after

- a) the objective of the risk assessment has been clearly defined;
- b) the elements of the system that must be considered to address this objective in a rigorous way have been identified.

The Table below extracts five key aims apparent in both the Regulation and its accompanying documents.

Table 1 – Classification of the aims of the Regulation:

Sufficient supply of gas (physical security)
Solidarity and coordination at regional level
Economic approach to security
Establishing a clear framework of roles and responsibilities of the different actors
Environmental concerns

The key message coming from table 1 is that the Regulation can be synthesised through five main aims. The first three have a direct impact on the issues that must be addressed in the national Risk Assessments:

1. *Sufficient supply of gas (physical security)*. Both Regulation 994/2010 and the previous Impact Assessment state clearly that their main goal is to establish an institutional framework to ensure a sufficient continuous supply of natural gas, particularly in case of difficult climatic conditions and in the event of disruption. The view behind this “physical” approach to gas security, which is somewhat independent from the “economically” optimal level of security (specific to each country / region), is that the weaknesses made evident in the January 2009 gas crisis must be tackled as soon as possible.

2. *Solidarity and coordination at regional level.* Regulation 994/2010 acknowledges one of the outcomes of the public consultation on the revision of the 2004 Directive, showing wide consensus amongst EU institutions about the need for cooperation at regional level: recent experience has demonstrated that there is a clear risk that measures developed unilaterally by a Member State may jeopardise the proper functioning of the internal gas market and the supply of gas to customers. Certain national emergency measures may in fact lower the level of security of supply in another Member State. Such actions should be avoided. Therefore, it is necessary to provide for solidarity and coordination in mapping the possible risks on national and regional level and preparing prevention and response mechanisms to supply crises.
3. *Economic approach to security.* Throughout the whole Regulation it is repeated several times that the internal gas market and effective competition within that market offer the Union the highest level of security of supply for all Member States, provided that the market is allowed to function fully in the event of disruption of supply affecting a part of the Union. Strictly related to this view, the need for a general economic approach to gas security is often stated:
 - security of gas supply must be strengthened at the lowest cost, without imposing unreasonable and disproportionate burdens on natural gas undertakings;
 - the ultimate goal is to avoid a disruption of gas supply that can have a “severe social impact”, which is not necessarily highly correlated with the uninterrupted physical quantity of gas entering into the system. This means that the question is more to find the country/region specific “acceptable” level of risk.

Two further aims can be identified in the Regulation, with an important impact on the issues that must be addressed in the Risk Assessments:

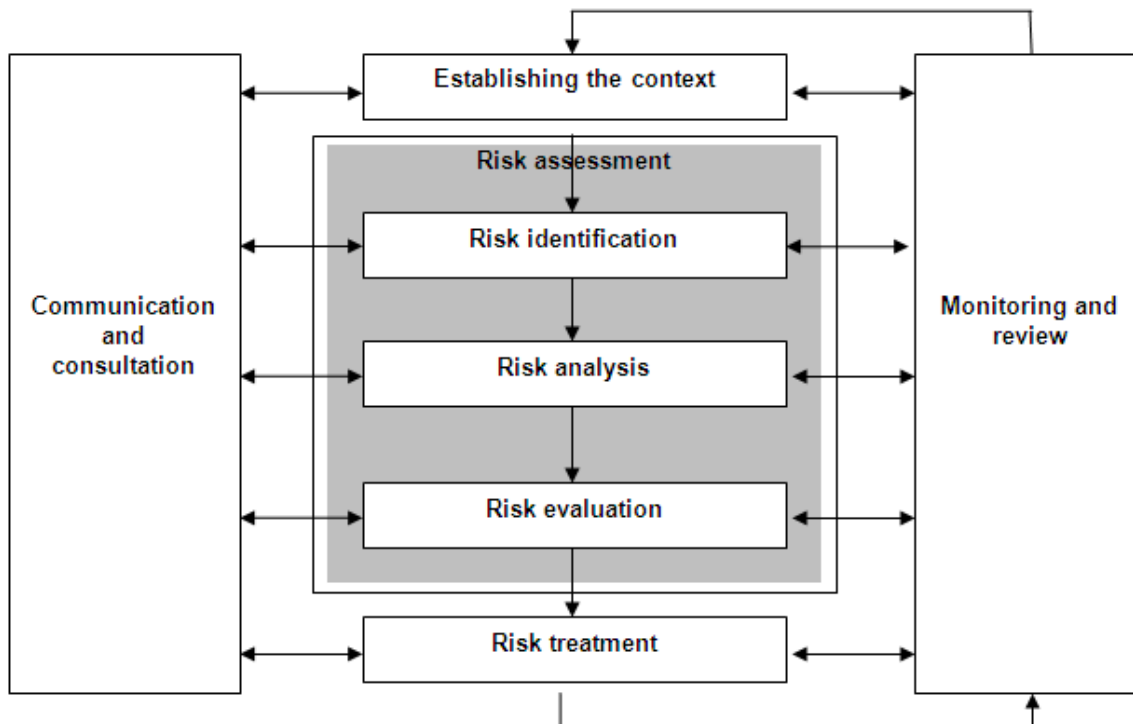
4. *Establishing a clear framework of roles and responsibilities of the different actors.* The Regulation asks each Member State to designate a Competent Authority that ensures the implementation of the measures. The list of Competent Authorities shall be public, therefore it will be clear which authority or body is responsible in a certain Member State. The Regulation reiterates that natural gas undertakings should be given opportunity to tackle the negative consequences of a disruption as long as possible.
5. *Environmental concerns.* Two articles of the Regulation state that the environmental impact of the proposed demand and supply-side measures (in the National and joint Preventive Action Plans) should be taken into due account. And preference should be given as far as possible to measures with the least impact on the environment.

3 Proposed Risk Assessment framework

Risk Assessment has been developed along the last decades until becoming a mature subject in the scientific and technical literature. Thanks to that degree of maturity, the scientific and technical community has been able to develop standards which provide an adequate framework to perform structured Risk Assessment studies, most remarkably *ISO 31000*. In addition to this key reference, the *ISO 31010* develops further, in much more detail than *ISO 31000*, the components of Risk Assessment. Moreover, *ISO Guide 73* contains the definitions for the most frequently used terms in Risk Management. These two standards and the mentioned guide have been taken as the main elements to propose a RA structure to implement the requirements in Article 9 of EC Regulation 994/2010.

According to *ISO 31000* (see annex 1 for a short summary) and *IEC/ISO 31010*, “Risk Assessment” is at the core of “Risk Management”, preceded by the ‘Establishing the context’ step and followed by “Risk Treatment:”

ISO International Standard Risk Management Framework



Basically, a Risk Management process involves understanding the system under study, assessing its associated risk, designing strategies / treatments to reduce the risk and making decisions about the adequate strategy to adopt (including the option of avoiding any action oriented to reducing the risk). The step addressed in this document is the Risk Assessment. Nevertheless, *establishing the context* is a mandatory and unavoidable step that contributes important inputs to the Risk Assessment. Risk Treatment is closely related to the preventive action plan, which will be dealt with in another document.

The next two sub-sections address respectively the ‘Establishing the context’ phase and the Risk Assessment.

3.1 Establishing the context

According to ISO 31000 (2009),

“By establishing the context, the organization articulates its objectives, defines the external and internal parameters to be taken into account when managing risk, and sets the scope and the risk criteria for the remaining process”

Establishing the context involves a set of activities related to setting the global process. Particularly it involves understanding the reasons to perform the Risk Assessment (e.g. adhering to the Regulation), all the parties involved in the process, the relations among them and the responsibilities, the decision making process and many other organisational tasks. Nevertheless, two key components of ‘establishing the context’ must be stressed: the characterisation of the system and the definition of Risk Criteria. Both subjects are dealt with in the next two subsections.

3.1.1 Parameters of the national gas system

The EC gas regulation calls for national and regional Risk Assessments. The scope of the Risk Assessment includes all the components of the natural gas supply chain. The following “relevant characteristics of the gas system” (Article 9) can be analyzed according to a sub-group of data/indicators which help to define the structure and parameters of the system. This information can be used as a proxy for determining the level of risk/exposure to supply disruptions. Annex 2 provides a more detailed discussion of some of the data listed below, and also presents a method for calculating aspects such as diversification, import dependence, or storage capabilities. Broadly, the parameters of the gas system can be categorised according to (a) market aspects; (b) infrastructure; (c) utilization and contracts; (d) the institutional framework; and (e) the regional context.

Following best practices, the categories below provide a list of some key elements that are taken into account when assessing risk in the national gas system.

A) Market

The following list of market-related factors is not exhaustive; it only refers to those elements of the market that affects or is relevant to the Risk Assessment. Both sides of the market are considered – demand and supply.

Demand	Supply
(average/monthly/peak/seasonal)	
Current and projected gas demand (up to 2020)	Current and projected gas supply (in the context of TPES)
Demand of transformation sector	Total production
Total final gas consumption (by sector - industry, transport, residential, district heating, power generation and commercial) and role of gas in the different sectors	Total imports (+ number of import sources)
Current and projected gas demand in primary energy mix	Total exports
Demand from interruptible/protected customers/district heating, average and peak day consumption (1-in-2, 1-in-20, 1 day, 7 days, exceptionally high gas demand throughout a longer period)	Gas quality (calorific value)
Voluntary/enforced firm load shedding	Number and market share of major energy firms
Level of market opening (proportion of wholesale/retail market open to competition ²⁸)	Level of supply diversification (can be expressed using Herfindahl-Hirschman Index, see annex 2)
Customer fuel switching capabilities, e.g. distillate backup for CCGT (industry, tertiary, household), alternative (obligatory) fuel stocks of certain consumers	Level and possibilities of cross-border flows/trading (contractual, physical bottlenecks)
Proportion of protected customers in total gas consumption	IGAs, long-term contracts
Gas prices for industry and power generation (regulation, evolution & volatility)	Number of suppliers, importers, TSOs, market concentration
Gas prices for households (regulation, evolution)	
Number/capacity of gas-fired power plants	
Age/maintenance of conversion facilities	

²⁸ Again, the HHI index or an equivalent indicator could be used, see Lewiner, C, ed., “European energy markets observatory”, *Capgemini*, 10th Edition, November 2008, p. 50 at http://www.capgemini.com/m/en/doc/0811_EEMO10_FullReportEN_corrections.pdf

Market description in the literature

Poyry 2010a (ch. 2 and 3) and Lithuania RA (ch. 2) are examples of descriptions of the current market situation at national level in terms of gas supply and demand, both current and projected (medium/long-term), with a good level of granularity: indigenous production, annual and peak demand at sectoral level, demand profile (Poyry 2010a/b), flexibility of the system in the event of a shortage (distillate backup and industrial and commercial demand side response could be utilised, with explicit assumptions on the market's potential for demand side response).

In most of the studies based on models a similar detailed description of the national/EU gas market is not explicit, but implicit in the modelisation of the gas market (or taken from external public sources, like IEA).

B) Gas infrastructure

Gas infrastructure refers to the physical infrastructure in place to produce, import, process, transmit, and distribute gas (here 'capacity' rather than 'flows' should be taken into account). Gas infrastructure includes the gas transmission network including interconnectors as well as production, LNG, storage, transformation and distribution facilities.

Pipelines	LNG	Storage	Production
Number of border transmission entry and exit points (pipelines)	Import capacity of LNG facilities	Maximal technical storage deliverability (withdrawal rate)	Maximal technical production capability
Maximal technical capacity of entry points (+ their country of origin)	Maximal technical LNG processing capacity (maximum sustainable send-out capacity)	Maximal working gas capacity	Reserves to production ratio
Physical bi-directional capacity (by pipeline)	Number of LNG facilities ³²	Physical characteristics of storage sites (number/type – e.g. base load/peak load ratio) – short/long-term storages	Number/type of production facilities ³³
Number of compressor stations along transmission lines ²⁹	Cross border LNG capacity/commitments		Planned investments
Number of gas metering stations	Planned investments	Cross border storage capacity/commitments	Age/maintenance of production facilities
Control stations and SCADA systems (+backup)	Age/maintenance of LNG facilities	Planned investments (+ age/maintenance of storage facilities)	
Planned investments ³⁰			
Age/maintenance of pipelines ³¹			
Internal bottlenecks, other upgrading needs in the national transmission system			

²⁹ This also provides an approximation of the total length of transmission lines; if possible, the energy source for the compressor station should be provided

Infrastructure description in the literature

The Alaska Risk Assessment (ARA) project, whose focus is on the safety of infrastructures, includes a very detailed description of the gas and oil regional infrastructure (ch 4). Even though less technically comprehensive than the Alaskan report, the technical details included by Poyry 2010a, Lithuania RA (national level) and EWI (EU level) describe all the current and projected physical supply infrastructures: production, storage, pipelines and interconnectors, LNG. In the remaining studies based on gas models the description of national/EU gas infrastructures is included in the models. The ENTSOG European Ten Year Network Development Plans (for 2010-2019 and 2011-2020) are among the public sources often used for projected infrastructures.

C) Infrastructure utilization and contracts

C.1) Utilization

Utilization relates to the volume and direction of gas supplies flowing throughout the system. Utilization differs according to different time periods (e.g. peak/seasonal/daily demand).

Pipelines	LNG	Storage	Production
Annual/peak incoming and outgoing flows	Annual/peak import flows from LNG terminals	Annual/peak volume of stocks	Annual/peak production
Annual/peak reverse flows	Annual/peak send-out flows of LNG	Annual/peak withdrawal rate	Remaining resources, unconventional resources
Annual/peak utilization rate (for each pipeline – bottlenecks can be identified)	Annual/peak utilization rate (for each LNG terminal)	Annual/peak utilization rate	Actual gas reserves Depletion rate

C.2) Contracts

Supply contracts are an integral part of determining the gas system's flexibility. The duration, type and exact terms of contracts should be taken into account. For pipelines, LNG, storage and production, the following should be taken into account:

- Number and type of contracts (long-term, short term, swap, use of spot market, volume of each)

³⁰ Planned investments should be assessed in line with ENTSO-G's Ten Year Network Development Plan (TYNDP) and should generally include those that are past the technical feasibility/planning phase and have been allocated financing and a timetable for construction

³¹ Maintenance could be expressed as the number of technical inspections (e.g. PiG runs in the case of pipelines) or the average number/cost of repairs.

³² Facilities include tankers, import terminals, regasification facilities and so on

³³ Can be divided between offshore/onshore sites

- Trading³⁴
- Flexibility/Liquidity³⁵

D) Institutional framework

In undertaking the risk assessment it is important to make a list of all the relevant stakeholders and the rules governing their activities. This is useful not only in identifying risk but also in being able to better manage unforeseen disruptions to supply (an integral part of the emergency/action plans).

- Stakeholders (e.g. competent authorities, interest groups, government ministries, energy firms, etc.)
- Roles and responsibilities (in addition to setting out the degree of adherence to the EU's 'three-level' approach to supply disruption management – market, national, then European response – member states are encouraged to specify whether TSOs have a system in place for coordinated dispatching in the event of a disruption).
- Regulatory framework (e.g. the institutions and rules governing relations between stakeholders)
- Legal arrangements for security of gas supply (Emergency provisions, disconnection order, enforced storage/stock capacity/withdrawal)
- Level of unbundling (legal, organizational)

Institutional framework description in the literature

Poyry (2010a, ch. 2 and 3) describes the regulatory regime for distillate backup capacity at power generation and industrial and commercial interruptible load. It also describes the investment drivers and barriers for gas infrastructure, storage and distillate backup investment in particular. RA of Lithuania (2010, sections 2.1.3, 2.1.4, 2.1.5) describes the regulation of the gas sector, with special focus on the applicable measures to safeguard supply security: storage requirements, interruptible consumers, procedures on energy supply to consumers in case of extreme events.

In the studies based on gas models the description of national/EU institutional context is embedded into the models. However, most models assume efficient markets, implying that technically available capacity and alternative supplies are available when required.

E) Regional context

³⁴ Trading refers to how gas is exchanged (e.g. through financial/physical market) and is affected by market liquidity, level of commodity trading versus bilateral market contracting, pricing through hub-trading, regulation or indexation, and so on. For a recent article on pricing developments in Europe, see Stern, J and Rogers, H, "The transition to hub-based gas pricing in continental Europe", Working Paper Energy Economics, Oxford Institute for Energy Studies, March 2011 at <http://www.oxfordenergy.org/2011/03/the-transition-to-hub-based-gas-pricing-in-continental-europe/>

³⁵ Flexibility refers to the ease with which contracted flows can be increased or decreased due to externalities (and it is crucially linked to the physical spare capacity of pipelines).

In addition to some of the cross-border data considered above (e.g. entry/exit points on pipelines, LNG, reverse flows, shared storage, etc), some additional cooperative instruments on a regional level should be considered in undertaking risk assessment:

- Describing existing cooperation mechanisms among TSOs (including planned cross-border investments)
- Regional emergency exercises
- Regional N-1

3.1.2 Establishing Risk Criteria

Establishing Risk Criteria means setting limits that help in determining whether the system is exposed to an either unacceptable or to an acceptable risk level. Risk criteria involve the two components of risk: likelihood (also referred to as ‘probability’) and damage (also referred to as ‘impact’ or ‘consequences’); see section 3.2. The Regulation does not mention explicitly what the measure of damage should be in undertaking a risk assessment, but it stresses the importance of supplying gas to ‘Protected Customers’. Particularly, the RA (article 9a) needs to apply the standards specified in Article 6 (the ‘Infrastructure Standard’) and Article 8 (the ‘Supply Standard’). These standards, which can be calculated using the data provided above, can be used as minimum acceptable risk criteria:

- The **Infrastructure Standard** is based on the N-1 formula. It is used to indicate the ability of the gas system to cope with the disruption of the largest gas infrastructure.
- The **Supply Standard** stipulates that gas supply needs to be ensured for protected customers in the event of several cases:
 - a) extreme temperatures during a seven-day peak period,
 - b) any period of at least 30 days of exceptionally high gas demand, and
 - c) for a period of at least 30 days in the case of the n-1 scenario during average winter conditions.

All this bring us to suggest three different, although closely related, possible measures of damage/impact

- Non-supplied gas to protected customers (evolution over time),
- Time during which the lack of gas supply persists, and
- Total non-supplied gas to customers (integral of the first one over time)

Based on these measures of damage/impact, and taking into account pertinent likelihoods, MS may define their respective risk criteria.

Nevertheless this is not the only set of measures of damage/impact that can be considered. According to the analysis shown in section 2, if a particular MS decides to take into consideration economic/financial potential damages, other measures of damage may be defined and used to set Risk Criteria. An economic approach is in fact adopted also by Regulation

994/2010, and by many scientific studies as well: to strengthen security of supply at the lowest cost, the goal is to find the level of risk which is “acceptable” for the specific system under analysis.

Poyry (2010a,b), UKERC (2010), CPB (2006), Oxera (2007) carry out cost/benefit analyses of possible options to reduce the cost of insecurity, by comparing the economic impact of supply interruptions and the benefits of possible security measures.

Risk Criteria in the literature

Two main approaches to risk criteria can be identified, one focusing on "rigid" standards to secure physical flows of gas, another one following a more flexible economic approach:

A) Standards, like the Infrastructure Standard and the Supply Standard established in Regulation 994/2010, can be used as minimum acceptable risk criteria.

- All the three Baltic State risk assessments (Estonia RA, Latvia RA and Lithuanian RA) include a transparent description of the calculation of the N-1 constituents. The result is that Latvia is well above the threshold of 100%, while Estonia and Lithuania fall short of it, with Estonia being able to fulfil the requirement if only the gas demand of the protected customers is considered.*
- The calculation of standards, if apparently straightforward, requires in fact a clear definition of the meanings of its constituents. An example is the calculation of the Supply standard established by Regulation 994/2010, for which some key variables, like for instance the “extreme temperatures during a 7-day peak period”, need a clear definition.*

B) Three examples of quantitative assessments based on economic risk criteria are the following:

- Poyry (2010a,b) establish as a benchmark for the assessment the “expected annual average cost of energy unserved”. After estimating the probabilities of unserved energy in a wide number of situations (mainly different gas demand and supply levels), the “economic impact” of a loss of load is estimated through the impact to GVA (Gross Value Added) of the unserved energy volumes.*
- Oxera (2007) and CPB (2006) follow a different approach: instead of establishing a threshold for a selected variable, they carry out cost/benefit analyses of possible alternative measures to reduce the cost of insecurity, by comparing the economic impact of supply interruptions and the benefits of possible security measures:*
 - Oxera compares alternative options to increase security based on their cost of implementation and the expected costs of forced outages (calculated as sum of probability of interruption times cost);*
 - in CPB (2006) the benefits of possible security measures (estimated through an energy market model) are measured though the costs incurred by a disruption; but as the expected efficiency of policies depends on the expected probability of uncertain future events which are nearly impossible to determine, “break event frequencies” are calculated for each security measures.*

An interesting common result of these different studies based on an economic approach to security of gas supply is that the possible options to increase the security of supply are rarely found cost-efficient.

A last further option to establish risk criteria is based on the use of indicators (ECN, IEA/Ecofys), whose aim is representing through just one or few figures the “diversity” of the energy system, a proxy for the expected impact of a crisis both in terms of physical flows and economic costs.

3.2 Risk Assessment

The word 'risk' has already been used several times in this document, but no formal definition has been provided so far. Quite frequently, risk is defined as probability times damage (or impact, or consequences, see fourth column in the table in Annex 5). Essentially this means that a measure of risk has to account for potential consequences and weigh them with their corresponding probabilities (likelihoods). In the following paragraphs another more operational definition of risk will be shown.

ISO 31010 indicates that Risk Assessments attempt to answer the following fundamental questions:

- What can happen and why?
- What are the consequences?
- What is the probability of its future occurrence?

Kaplan and Garrick (1981) showed that a formal answer to these three questions requires describing risk through the use of a set of triplets³⁶:

$$R = \{ \langle s_i, \varphi_i, y_i \rangle \} \quad i = 1, 2, \dots, N, \quad (1)$$

where

1. s_i represents scenario i in the set of N scenarios considered.
2. φ_i is the probability of scenario i.
3. y_i is the potential consequence under the conditions of scenario i.

This constitutes a formal mathematical definition of risk, although it does not account for all sources of uncertainty (for a more detailed definition that accounts for all sources of uncertainty see annex 3). Under this definition each scenario is characterised by its probability and its consequence(s) (one or several consequence variables may be considered, but only one possible value of each consequence variable is considered). Adopting this definition of Risk means that all possible scenarios must be identified and the probability of each must be estimated. Moreover, for each scenario, the consequence(s) for the system must be assessed. In order to do all these tasks, ISO 31000 and IEC/ISO 31010 divide the Risk Assessment in the following three steps:

- Risks identification
- Risk analysis
- Risk evaluation

³⁶ Kaplan S, Garrick BJ. "On the quantitative definition of risk". *Risk Analysis*; 1(1), 1981: 11-27 at <http://onlinelibrary.wiley.com/doi/10.1111/j.1539-6924.1981.tb01350.x/abstract>

The following sections will describe these steps in the context of the Regulation's requirements.

3.2.1 Risk identification

According to ISO 31000,

“The organization should identify sources of risk, areas of impacts, events (including changes in circumstances) and their causes and their potential consequences. The aim of this step is to generate a comprehensive list of risks based on those events that might create, enhance, prevent, degrade, accelerate or delay the achievement of objectives.” (ISO 31000, pg. 17)

The set $\{s_i\}_{i=1,\dots,N}$ considered in the definition of risk must contain all possible scenarios, which means all possible system contingencies – in terms of a physical loss of gas supply as well as the various technical, political, economic and natural factors associated with this contingency (as either causes or consequences thereof). In other words, the set of scenarios should be exhaustive. Additionally, the scenarios must be mutually exclusive; the occurrence of one of them precludes the occurrence of any other one. Fulfilling both conditions means that the addition of the probabilities of all scenarios is 1. In principle, the most likely situation is that the gas system undergoes either no perturbation or small perturbations that do not prevent it to perform the assigned tasks. This would be the normal evolution scenario. In addition to the normal evolution scenario, the really important scenarios have to be identified: scenarios with non-negligible probability and non-negligible consequences. The scenarios considered may span a wide range of different circumstances, from technical failures in the physical pipeline network to political problems or even policy or market failures.

The first task to design an adequate set of scenarios is the identification of all possible sources of risk (Risk Identification). This is a very important task because missing some relevant source of risk may produce a lack of exhaustiveness in the set of scenarios and therefore may lead to risk underestimation.

Several risk identification techniques exist in the literature. IEC/ISO 31010 provides a detailed overview and a comparison of risk identification techniques. In particular, the authors of this report consider the following techniques as the most suited to deal with risk identification in the gas sector:

- a) brainstorming
- b) structured or semi structured interviews
- c) check lists
- d) Hazard and operability analysis (HAZOP)
- e) Failure mode and effects analysis (FMEA)

Annex 4 provides a short description of each one, highlighting their main characteristics, when they are most useful, the types of inputs needed and outputs obtainable, and the most remarkable strengths and limitations.

A useful starting point in any risk identification technique is to condense and classify all the possible sources of risk. The relevance of a classification rests on two factors: it helps thinking on sources of risk that share some commonalities, making thorough risk identification more likely and, usually, it helps to realise that each category of risk requires a different analytical approach.

A basic and classical categorisation of sources of risk consists in classifying them as intentional and non-intentional. Sources of risk that belong to the former category are called 'threats', while those that belong to the latter are called 'hazards'. Another possible categorisation attending to the origin of the sources of risk is:

1. Technical

- a. Hazards (e.g. unintentional failure of infrastructure, ICT breakdown)
- b. Threats (e.g. intentional sabotage/attack)

2. Political

- a. Hazards (e.g. civil unrest, war)
- b. Threats (e.g. targeted attacks on gas infrastructure, strikes)

3. Economic

- a. Hazards (e.g. gas price volatility)
- b. Threats (e.g. commercial dispute, monopolization of market)

4. Environmental (e.g. natural hazards)

- a. Hazards (e.g. hurricane, earthquake, flood, landslide, etc.)

An alternative categorisation of sources of risk is the one suggested in the EC FP-7 research project EURACOM, which considered four major categories: intent, failure, nature and cascade (see table 2 to find sources of risk in each category).

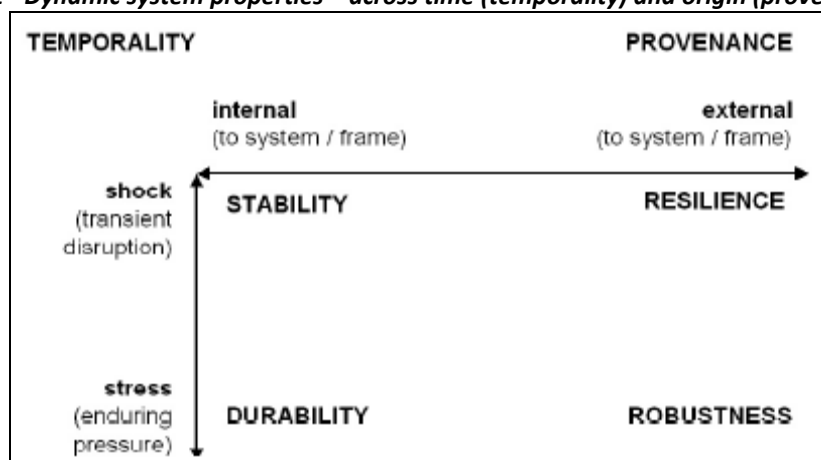
Table 2 – Categorisation of sources of risk according to EURACOM project; EURACOM, Del. 2.3.

Intent	Failure/Accident	Nature	Cascade
Acts of Terrorism	Negligence	Extreme weather conditions	Loss of power supply/utilities/services
Acts of Vandalism	Mistake	Pandemic (Flu/etc)	Loss of Telecoms
Theft (copper/metals)	Impact (e.g. vehicle against pylon/pole)	Geological	Loss of Energy Supply to the Electricity Transmission Network (Interconnector / Generated supply) Loss of 'black start' capability
Theft (equipment)	Ingress of Water	Fire	
Industrial action	Explosion	Flood	
Targeted Cyber Attack	Disclosure of information (Theft/Leakage)	Solar Activity	Loss of pumped storage capacity
Virus/Trojans	Equipment malfunction or failure		
EMP	Chemical (spillage)		
Act of War	Loss, unavailability or turnover of personnel		
Diplomatic Incident	Outdated and un-maintainable technology		

Another useful approach to classify sources of risk is according to their *temporality* (e.g. a sudden, short-term shock or a long-term stress) and to their *provenance* (internal or external), as well as according to their *physical* or *price* implications.

Transient *shocks* can be differentiated from more enduring *stresses*. Each of them may originate either inside or outside any given construction of the gas system (Scoones et al. 2007, Stirling 2009). The distinction is of importance because the strategies for maintaining the gas system may be very different for each case. An alternative denomination for shock is event, while an alternative denomination for stress is process.

Fig. 1 - Dynamic system properties – across time (temporality) and origin (provenance)



It is useful to differentiate an event with a prevailing *price* component from an event with a prevailing *physical* component:

- the former is more relevant in markets where prices are allowed to adjust in response to changes in demand and supply, so that the risk of physical unavailability is reduced to extreme events; the prevailing energy security concern is related to prices not set competitively or overly volatile; the international oil and coal markets can be included in this category (IEA 2007);
- on the contrary, physical unavailability is the main concern in markets where prices are regulated or pegged on other commodities, so that price movements cannot contribute to balance supply and demand; the gas markets in most European countries fall in this category (IEA 2007).

The final output of the Risk Identification phase should be a comprehensive list of events and processes that may push the system to undesired consequences. Ideally, each term in the list should be accompanied by a set of potential effects on the system. It is also of interest to identify for each event or process what other elements of the list could be affected by its occurrence (either by modifying its probability of occurrence or by affecting the potential consequences).

Risk identification in the literature

SECURE (Checchi et al 2009³⁷) is an example of a relatively comprehensive description/mapping of the wide range of risks facing the EU energy system, considering technical, (geo)political, economic, geological and natural/environmental risks. The study includes both short-term shocks and long-term enduring shifts.

³⁷ Checchi, A; Behrens, A; Egenhofer, C, “Long-term energy security risks for Europe; a sector-specific approach”, CEPS Working Document, No. 309, January 2009 at <http://www.ceps.eu/book/long-term-energy-security-risks-europe-sector-specific-approach>

REACCESS (2008) identifies and categorizes risks on the base of a historical description of all the short-term shocks materialized in the global energy markets during the last sixty years.

ECN (2007) also proposes a check-list system for identifying risks, breaking them down in terms of the part of the supply chain in which they appear.

National studies, like the RA of the Baltic states and Poyry (2010b, ch. 4) select the risks considered more significant for the country, on the base of a discussion of their gas systems. They focus mainly on short-term shocks, considering both risks coming from inside the national gas system and external risks.

Some studies take risks as a given, building them into their assessment of probabilities of contingencies or failures. For example, Oxera (2007) models risks as the annual probability of a) operational outages, b) outages of transit routes, of terminals capacity, c) of capacity storage, that are independent to the specific sources of risks.

ARA (2009) divides the system into nodes and considers a comprehensive list of technical failures and natural hazards that can affect each node. These events (failures and hazards) are screened according to their probability occurrence and potential consequences to the whole system.

3.2.2 Risk Analysis

According to ISO 31000

“Risk analysis involves consideration of the causes and sources of risk, their positive and negative consequences, and the likelihood that those consequences can occur. Factors that affect consequences and likelihood should be identified.”

The objective of the risk analysis is to formally define scenarios as combinations of the identified events or processes (the whole range of hazards and threats; shocks and stresses) that may jeopardise the correct system performance, estimate their likelihoods and assess the consequences under the conditions of each scenario, either in terms of non-delivered gas to protected customers, or in terms of any other undesired effect. In addition to these typical elements of a formal Risk Analysis, and according to article 9 of the Regulation, the results of the Infrastructure Standard (article 6) and of the Supply Standard (article 8) must also be included. Correlated risks with other MS must be identified. These may be further elaborated in a Regional Risk Assessment. Finally, the risk associated to the system may evolve over time. It is of interest to study that evolution considering different time frames. It is to be noted that the Risk Assessment should be updated every two years. The following subsections are dedicated to these subjects.

3.2.2.1. Formal Risk Analysis

A formal Risk Analysis may be structured in three phases:

- Scenarios definition
- Probability/likelihood estimation

- Consequences assessment

A) Scenarios definition³⁸

As already mentioned elsewhere, the set of scenarios should be exhaustive (cover all possible system contingencies) and mutually exclusive (the occurrence of one of them precludes the occurrence of any other one). Each scenario is a meaningful combination of events and/or processes (the combination includes also the case of only one event or process), together with a set boundary conditions, that has non-negligible probability and/or consequences.

From a practical point of view, the number of scenarios that should undergo rigorous analysis should be relatively small. Each selected scenario must be representative of a set of scenarios that produce similar consequences. The probability of each selected scenario must account for all the non-addressed scenarios that it represents.

Scenarios definition is basically based on Expert Judgement, although in some technology areas the use of event trees for this task is widespread (see annex 9). The starting point is the set of events and processes selected in the risk identification phase. Probabilities of occurrence and expected consequences must be taken into account in the construction of scenarios. Defining thresholds on probabilities and potential consequences may be of help to screen out scenarios that do not contribute significantly to the total system risk.

The result of this phase is a list of scenarios with their respective probabilities. Each scenario should be accompanied by a clear and detailed description that involves all assumptions and boundary conditions considered in its definition.

Scenario definition in the literature

A basic problem of any scenario definition is the difficulty in attaching a probability to each scenario.

ARA (2009) is the only example of an attempt to compile a comprehensive set of scenarios selected through a rigorous methodology (fault trees and event trees). This is due to the more narrow scope of the analysis, limited to infrastructures.

On the contrary, the range of possible one-event impulses and gradually strengthening/declining forces that can exercise a negative/positive impact on the security of gas supply are too broad to be approached as “risks”, each one with its own magnitude and probability. As a consequence, most of the literature with a wider scope define disruptions in terms of “categories of crisis scenarios”, selected because they are reasonably likely to occur (often on the base of past experience).

In some case, like in Poyry (2010a), probability distributions are applied to each of these scenario categories (see next box on probability calculation in the literature). In most of the other cases, a limited number of scenarios are selected on the basis of their expected impact, as in the two following cases:

*a) EWI (2009) selects 12 main scenarios: 6 infrastructure scenarios * 2 demand scenarios (EWI/ERGEG low demand case and ENTSG high demand case), plus 6 sensitivities on Peak Day and 6 sensitivity on*

³⁸ It is convenient to stress the difference between scenario analysis and the use of scenarios in a risk assessment. The main use of scenario analysis is to give a broad perspective of how the future could turn out, trying to cover a large part of its possible variety. Usually a best case, a worst case and an expected case, in addition to other possible cases, are generated. In general, no attempt to estimate probabilities / likelihoods is done. This makes the great difference with the use of scenarios in the framework of risk assessment, whose identification is driven by probability and consequences.

Disruptions (Ukraine Transit / Algeria supply disruption). The six infrastructure scenarios are:

- *Reference: Nord Stream I only (but no other major projects)*
- *Nord Stream II: Reference + 2nd line of Nord Stream*
- *Nabucco: Reference + Nabucco pipeline*
- *South Stream: Reference + South Stream pipeline (no midcat)*
- *DG-TREN: Reference + 2nd line of Nord Stream + Nabucco*
- *LNG Glut: DG-TREN + lower LNG prices*

b) The ENTSOG Ten-Year network development plan 2011-2020 defines three categories of scenarios

- *Reference case scenarios, accommodating different levels of demand (average/high), supply (average/high) and infrastructural capacity (FID / FID + Non-FID), and used as a benchmark for comparison with the other two categories*
- *Security of Supply scenarios, to assess the resilience of the network under a set of disruption scenarios or low storage deliverability, and under High Daily Demand condition for a one-day period (considering history, probability, season, frequency and duration of such occurrence as well as, where appropriate, geopolitical risks).*
- *Market integration scenarios, to assess how far gas coming from each supply source can flow into the European gas network.*

B) Probability/likelihood estimation

Probability/likelihood estimation may be either quantitative (numeric estimation of probabilities) or qualitative (soft likelihood estimation). The election of one or other choice depends on the availability of data, their quantity and quality. When almost no data are available, and their quality is either low or unknown, likelihoods may be estimated in a qualitative manner; otherwise quantitative assessments should be done.

When the option selected is the qualitative one, a likelihood scale should be defined. The definition of classes in the scale should be as accurate as possible, which is not a simple task, given that qualitative scales are used under large uncertainty conditions. The number of classes should be neither too large (difficult to justify) nor too small (too little information). As an example, in the EURACOM project, the following five-class scale is suggested:

- **1 Very low probability** (It is extremely unlikely that the incident will occur – no experience in the gas sector)
- **2 low probability** (It is unlikely to occur – very limited experience in the gas sector)
- **3 Medium probability** (It is a likely event – similar accidents have been reported in the gas sector)
- **4 High probability** (It is very likely to occur – it has been experienced in most systems in the gas sector)
- **5 Certainty** (It will happen in the close future)

IEC/ISO 31010 quotes an application where also five classes are considered (likely, possible, unlikely, rare, remote). Some applications performed in the context of the Regulation consider between three classes (low, moderate, high) and five classes (the same as above)

In case the quantity and quality of data is enough, the following three generic strategies may be followed

- **Classical inference methods:** these techniques are suggested when plenty of historical or experimental data are available. In this case usual techniques as for example the method of moments or the maximum likelihood method is of use. See annex 6 for more details.
- **Bayesian inference methods:** these techniques are suggested when not many specific historical data are available, but some generic data may be of use. This could be the case for example if not much experience has been accumulated about a given facility, but similar facilities are available in other countries, which have accumulated long historical records. In those case, generic data from similar facilities/systems could be used to create a 'prior distribution', which could be combined with the likelihood obtained from the few historical specific records in order to generate the 'posterior distribution' for the quantity under estimation according to Bayes formula. See annex 6 for details.
- **Expert judgement (EJ):** these techniques are suggested when not many data are available. In this case, well-known experts would be asked to participate in a structured EJ exercise to provide their estimates. Usually, even under severe scarcity of data, experts are able to quantify their opinions in terms of probabilities, which is much more useful than providing soft qualitative likelihood estimates in qualitative scales. See annex 7 for more details about structured EJ protocols and techniques.

The three types of techniques mentioned may also be used to characterise any other parametric uncertainty that could arise in the Risk Analysis. This would be the case if a more complete definition of Risk is adopted (see annex 3) and system parameter uncertainties are accounted for explicitly. In such a case, parametric uncertainty should be characterised via estimation of the corresponding probability density functions by means of the adequate method among the three mentioned above.

In addition to the three aforementioned techniques, event tree and fault tree analyses (see annex 9) are of help to estimate the probability of scenarios when there are no relevant data about the scenarios themselves, but data about the individual events used to build the scenario are available.

In principle, the use of quantitative probability estimates is encouraged. The more quantitative the assessment is, the more useful their results become. Computations to calculate the probability of scenarios based on the occurrences of several events/processes or to calculate the probability of sets of scenarios are relatively simple. The same computations turn to be really ambiguous when the basic likelihoods have been estimated in a qualitative scale.

Probability calculation in the literature

ARA (2009) is the only example in which probabilities of scenarios are explicitly estimated through a rigorous methodology, i.e. fault trees and event trees. This study assigns failure probabilities to each failure mode in a node. The more likely occurrences are used to build proper scenarios; a Bayesian approach is adopted for estimating probabilities of failure.

Oxera (2007) builds assumptions on annual probability of operational outages, outages of transit routes, of terminals capacity, of capacity storage. A distribution of demand around the central scenario is also used, to derive annual and peak demand figures for 50 assumed gas years ranging from 1-in-50 warm to a 1-in-50 cold year. Poyry (2010a) also applies probabilistic distribution to the central supply and demand scenarios.

Estonia RA, Latvia RA and Lithuanian RA provide a qualitative distinction of risks in high, intermediate, and low levels.

C) Consequences assessment

There are two main ways to assess consequences of scenarios: the use of expert judgement and the uses of models. Models are the best tools available to the organisations performing the Risk Assessment; they include all the available knowledge about the system and are preceded by a large effort of verification and validation prior to their widespread use with forecasting purposes. The use of expert judgement is not well justified when models and data to study the system are available.

An issue to be solved by the implementers of the Regulation in each Member State is the selection of the measures of damage, as it was already mentioned in sections 2 and 3.1.2. In the next pages some advice is given about the modelling tools to be used depending of the measures of damage considered. We also discuss about the scales to use when summarising modelling results.

Modelling as a tool for consequence assessment

Models provide a crucial way of measuring the consequences of energy insecurity. This section presents a framework for the modelling of security of gas supply, i.e. for addressing it in a rigorous and as far as possible quantitative way.

One's choice of model depends on all the factors taken into account in the risk assessment thus far: the identification of the objectives of the assessment (i.e. the definition adopted for energy security and the acceptable level of risk by referring to the wider or narrower possible interpretation of the Regulation; the characterisation/parameters of the system (section 3.1); and the categorisation of threats/hazards (section 3.2.1)

To select the methodology/model to be adopted for the analysis, a rigorous procedure could imply the following three steps:

1. *Identify the methodological requirements to assess the objectives in a quantitative way, i.e. the relevant issues for analyzing and modelling the gas market.*

Different energy security threats and different insurance strategies have their own specific characteristics. To clarify the methodological requirements to address “properly” each of them, a framework normally used to classify energy-economy models has been adopted (see Annex 8). This approach helps to identify the elements of the system that must be considered in any specific assessment, and makes evident what are the characteristics of the “ideal” tool to be selected.

2. *Identify the models/tools fulfilling the minimal requirements to address the different objectives included in the Regulation.*

To do so, a table provided in the annex uses the categorization defined in the previous step (Table 8.1, Annex 8) to define the specifications that should be taken into account to “properly” address the targets of the regulation. Broadly, its purpose is to distinguish different methodological options for modelling the gas system, depending on the specifications of the Regulation. After all, the choice of model specifications/parameters depends on one’s interpretation of the Regulation. In other words, the model can take into account:

- only the physical provision of natural gas
- the requirement for solidarity and regional cooperation during supply disruptions
- the economically-optimal level of gas security (e.g. by taking into account the costs and benefits of energy security projects as per the Regulation’s suggestion)
- the environmental impact of security measures

As discussed in section 2, these characteristics can be ordered in terms of increasing levels of methodological complexity (by virtue of taking into account more and more factors/requirements) and decreasing levels of relevance to the risk assessment. As such, the first two conditions are considered the minimum that must be taken into account by any model/tool used for assessing risks to natural gas security in the European Union.

Tables 8.1 and 8.2 in the annex demonstrate how different approaches to the regulation can impact on the model/tool characteristics, by identifying the elements of the system that must be considered in any specific assessment: it shows how the simulation of the purely “physical” approach to security of gas supply (first target of the regulation) requires (among others characteristics):

- an *energy system* and *multi-energy market* approach, in order to consider and simulate in a quantitative way the substitution possibilities throughout the whole energy system;
- for the same reason, a *detailed description of the technological characteristic of the system along the whole supply chain*;
- as part of this detailed technological description, a strong *characterization of the network*, necessary to simulate the way gas flows inside the region under consideration;
- a *highly detailed* approach in terms of *time granularity* if/when the focus is on the assessment of the impacts of a short-term shock;

Table 8.2 shows how, if taking into account solidarity and regional cooperation during a supply disruption is considered inescapable (indeed a requirement strongly stressed by the new regulation, as shown in section 2 of this report), then a supra-national / regional approach becomes a further necessary requirement. As a matter of fact, a geographical boundary of the system under study corresponding to the national level can be acceptable for a national RA assessing the possible impacts of a crisis on the national system. But it would fall short of addressing the need for solidarity and regional cooperation during a supply disruption.

Last, the table shows the further requirements imposed to the methodology by the decision to address into the analysis the third main target of the regulation, i.e. the need to adopt an economic approach to gas security. This implies that any assessment should be able to:

- simulate the functioning of market mechanisms;
- take into account all the relevant information to identify the (regional/country specific) economically-optimal level of gas security, so as to strengthen security of gas supply at the lowest cost, and “without imposing unreasonable and disproportionate burdens on natural gas undertakings”.

As implied in section 2, the last two objectives of the regulation have a more limited impact on the selection of the requirements of the methodology to be adopted. However, if the assessment aims to select energy security strategies with the lowest environmental impact, the selected methodology should be able to produce quantitative estimates of the environmental impact of a policy option.

3. *to survey and classify the existing quantitative tools/models used to analyze energy/gas security issues, to select the tool most suitable according to the objectives.*

The last step for the selection of the tool/model to be used for the assessment is to match the methodological requirements identified in the previous steps with the currently available tools/models.

The survey of models provided in annex 8 does not aim to be comprehensive. Its aim is instead to show how the wide range of models available in the main literature can be differentiated on the basis of the theoretical framework proposed above. As the choice of the issues to be simulated are strictly country/region dependent, any Member State can either carry out its assessment by developing a model with the desired characteristics or consider the possibility to use one of the existing model.

Consequence assessment in the literature

Several different modelling approaches can be adopted to assess the consequences of crisis scenarios:

- *Energy system models (REACCESS, Secure, UKERC) aim to represent all the interactions between all the components of the wide energy system. In order to obtain a proper representation of each of these components UKERC (2009) makes use of an energy system model as first step of a chain of three separate models with complementary characteristics, best suited to address specific purposes: 1) MARKAL-MED UK, a linear optimisation model which covers the entire UK energy system and can address interactions between different parts of the energy system. 2) WASP electricity generation planning model, to explore in more detail the levels of generation investment needed to maintain reliable supplies. The WASP model is fed electricity demand assumptions from MARKAL-MED. 3) the geographically explicit Combined Gas and Electricity Networks (CGEN) model, to assess where electricity generation capacity should be located and how much gas and electricity infrastructure (wires, pipes, gas storage, import terminals) should be constructed. It is another cost-minimising model which is fed results from both MARKAL-MED and WASP.*
- *Partial equilibrium economic models of the gas market are not able to represent these interactions, but are more detailed with respect to some characteristics of the gas market: TIGER is a good example of a detailed model for the assessment of the physical impact of supply crises, while Pegasus is able to assess the economic impact of a crisis.*
 - *TIGER, developed by EWI, is an economic based network (not "technical") simulation model, with a Geocoded Database: Coverage EU-27, 600 Nodes, 900 Pipeline sections (based on TSO Maps, Capacity / Pressure / Diameter, Nearly all Entry-Points, Major Exit Points, Border point capacities), 200 Storages (Type, Max. injection / withdrawal, Working Gas Volume), 30 Terminals (Max. hourly / annual capacity, LNG Storage Capacity). Gas supply / demand / infrastructure projections are exogenous, based on data from European Commission / ERGEG / TSOs. The model minimize total cost of gas dispatch in the investigated year (2019) given infrastructure and supply, assuming an efficient EU downstream market and that all efficient and possible gas swaps are realised by TSOs. Technically available capacity is presumed to be made available to shippers efficiently according to market needs. TIGER identifies the physical need for network expansion, potential bottlenecks and the contribution of different infrastructures to SoS.*
 - *Pegasus ('Pan-European GAS + US') projects gas prices and flows and examines the interaction of supply and demand worldwide (17 European zones + US and Japan) on a daily basis, to estimate weekday/weekend differences, flows of the Interconnectors and gas flows in and out of storage in detail. Interconnection from GB to the Continent are modelled by minimising the cost of supplying gas to both zones, subject to both the capacity and the cost of transiting gas across the interconnectors. The major storage types are modelled accurately for each zone, each with its own injection and withdrawal rates, total storage capacity and cost of injection/withdrawal. The worldwide LNG market is modelled by considering all existing, under construction, proposed and conceptual LNG liquefaction projects worldwide, as well as LNG re-gasification terminals. Pegasus assumes perfect foresight, implying that alternative supplies are available when required. The combination of Pegasus with Prometheus, a stochastic model of the GB gas market, makes possible to estimate the economic impact of possible disruptions, by producing probability distribution of unserved energy and assessing their expected impact on the economy through a Gross Value Added analysis. For each disruption scenario Poyry (2010a) estimates not only their physical impact (through unserved energy, supply and demand, storage and LNG usage and DSR, capacity margins,...), but also the price impacts of a disruption and the GVA impact of unserved energy, the expected value of unserved energy, the price distribution for each day*

of the year.

Use of scales

As in the case of probability/likelihood scales, risk analysis practitioners are encouraged to use quantitative scales as much as possible. This is certainly the scale to be used when models are used to forecast system performance. In this case, the use of either linear or logarithmic scales depends on the dispersion of results for the different scenarios, albeit in principle logarithmic scales may be of much help. The use of quantitative scales allows greater accuracy in the presentation of results and in the decision-making process inherent to the Risk Treatment phase (preventive action plan design). In the case of using expert judgement for estimating results, either quantitative or qualitative scales may be used.

In case of using qualitative scales, a categorisation of results or definition of classes must be done. A balance must be found between the quality of the results provided and the accuracy. An intermediate number of classes is suggested (around five, see figure 2 in section 3.2.3.1).

The following categorisation has been suggested:

- **Minor** – when the impact of the risk leads to a disturbance in the supply which can be managed by market-based measures and supply to customers are not changed.
- **Noticeable** – when the impact of the risk deteriorates supply conditions but the market is still able to resolve the situation with solely market based measures and consumers are not forced to restrict or significantly change their usual consumption
- **Severe** – when the impact of the risk causes a serious supply disruption and emergency/non-market measures have to be introduced in order to provide supplies at least to protected customers.

Literature in the area related to the Regulation use between 3 and 5 classes, see Poyry (2010), Lithuania's Risk Assessment (2010), and ISO/IEC 31010, among other documents.

Acknowledgement of uncertainty in consequence assessment

In some cases, much uncertainty may be expected in the possible consequences of a scenario because of different reasons. In such situations, it could be of much interest a formal assessment of consequence uncertainty. Several methods are available in the literature, but certainly the most widespread general-purpose method to propagate uncertainties through a model is the Monte Carlo method, see annex 10. This method allows the estimation of the whole spectrum of possible consequences by means of estimating model input uncertainties, running the model under different values of input parameters and describing the consequences in statistical terms.

Acknowledgement of uncertainty in the literature

Poyry 2010a (section 4.3) performs a probabilistic analysis to estimate the diversity of possible incurred

unserved energy quantities (its probability density function) among other output variables of interest. This was done by means of assigning probability distribution functions to short term losses in different sources of supply and to variations in demand due to weather and other factors, and propagating uncertainties via Monte Carlo simulation using the adequate models.

3.2.2.2 Correlated risks and regional cooperation

Each MS is not a standalone actor in the European gas system, but rather belongs to a network full of interactions and feedbacks. The events and processes that happen in one MS and the measures that it adopts to cope with the effects of events and processes may have an important impact on neighbouring countries. These potential effects have to be found and estimated.

In principle there are two major sources of dependencies between different MS:

- The occurrence of events and processes (scenarios) that affect more than one MS (in the standard RA jargon, these could be called common cause failures). For example,
 - Adverse severe weather conditions affecting several countries
 - High prices in the spot market affecting simultaneously all countries
 - Failure of key infrastructures of common use (electricity grid blackout)
- The reliance on neighbouring countries for obtaining gas, e.g. problems in the physical flow of gas in a country propagating to downstream countries, or shared reliance on cross-border storage capabilities

Once national risk has been assessed, it should be possible to identify the interaction and correlation of risks with other Member States (Article 9d), particularly if the risk assessment methodologies are commensurable. This is possible by an analysis of the following:

- interconnections, including maximal interconnection capacity of each border entry and exit point
- cross-border supplies
- cross-border access to storage facilities
- bi-directional capacity

A joint risk assessment can be undertaken according to Annex 4 of the Regulation. Assessing the interaction and correlation of risks with other Member States is an important part of this step. The N-1 formula can form the basis of a regional risk assessment. For the calculation of the N-1 formula at regional level, the single largest gas infrastructure of common interest shall be used. The single largest gas infrastructure of common interest to a region is the largest gas infrastructure in the region that directly or indirectly contributes to the supply of gas to the Member States of that region and shall be defined in the joint Preventive Action Plan. The regional N-1 calculation can only replace the national N-1 calculation, where the single largest gas infrastructure of common interest is of major importance for the gas supply of all Member States concerned according to the joint risk assessment.³⁹

³⁹ Annex 1 (5) regulation

3.2.2.3 Timeframes

The system analysed evolves over time due to many different factors such as the depletion of sources of gas, the discovery of new sources, the development of new infrastructures, the degradation of old infrastructures not sufficiently maintained, and so on. This evolution may have a significant impact on the probabilities of scenarios and on their potential consequences. Therefore, it is of interest to extend the Risk Assessment to different timeframes, particularly if important changes are expected in the system. An *a priori* categorisation of timeframes that may be considered is the following one:

- **short-term:** existing risks and risks appearing within the coming 5 years
- **medium-term:** risks appearing within the coming 5-10 years
- **long-term:** risks appearing in more than 10 years

3.2.3 Risk evaluation

According to ISO 31000 (2009),

“The aim of this step is to assist in making decisions, based on the outcomes of risk analysis, about which risks need treatment and the priority for treatment implementation.”

Risk Evaluation is the phase where the Risk Analysis results are collected and put together. The target is to show the results in the most understandable possible way to facilitate the interpretation of results and the decision-making process to be done in the Risk Treatment phase (preventive action plan) and to be used for collecting risks on the regional level in case of the establishment of a joint Risk Assessment.

In principle, any clear presentation of results is enough, as for example the list of scenarios ranked according to either their likelihoods or to the assessed consequences, accompanied by any explanatory text (commonly called ‘risk summaries’).

Nevertheless, the probably optimal ways to represent results, depending on if the assessment has been either qualitative or quantitative, are respectively:

- The Risk Matrix
- The Complementary cumulative curve of the output (random) variable ‘damage’

3.2.3.1 The Risk Matrix

The Risk Matrix is the adequate way to represent results from a qualitative assessment. On the x-axis classes of consequences are represented (increasing damage from left to right). On the y-axis classes of likelihood are represented (increasing likelihood from below to above). The Cartesian product of both axes provides all the possible combinations of likelihoods and

consequences. A colour code (green – yellow -red) and/or number code (I-II-III-IV, etc.) indicates the severity of the combination likelihood-consequences. Each scenario is represented in the matrix using some code (numbers, letters, acronyms, etc.)

This type of representation allows a fast visual identification of most severe scenarios. Nevertheless, as it was already mentioned in the section 3.2.2.1, it is not easy to find what could be the global risk associated to a set of scenarios. For example, in fig 2, if we get as results of the Risk Analysis that four scenarios fall in the cell (severe, possible), it is not easy to deduce if the global risk associated to this set of four scenarios would fall in the same cell or if it should be moved upwards in the likelihood scale, getting into the ‘High’ Risk region.

Fig 2.- Example of Risk Matrix; ISO/IEC 2009

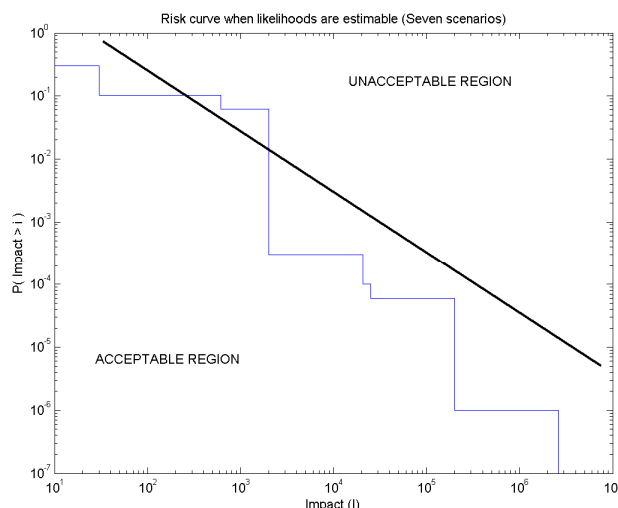
		Severity				Likelihood
Almost Certain	Medium	High	High	High	High	
Probable	Medium	Medium	High	High	High	
Possible	Low	Medium	Medium	High	High	
Unlikely	Low	Low	Medium	Medium	High	
Rare	Low	Low	Low	Medium	Medium	
		Insignificant	Significant	Severe	Major	Catastrophic

3.2.3.2 The complementary cumulative curve of the output (random) variable ‘damage’

The complementary cumulative curve of the output variable ‘damage’ is the adequate way to represent results from a quantitative assessment. On the x-axis consequences are represented (increasing damage from left to right). On the y-axis probabilities are represented (increasing probability from below to above). In fact, on the y-axis exceedance probabilities are represented (the probability that the damage exceeds any given value).

In order to create this representation, scenarios are ranked according to the consequences. Then, for each possible value of the consequences, the probability of exceeding that value is represented on the y-axis. As a result a stepwise function is obtained, like the one represented in figure 3.

Fig 3.- Example of complementary cumulative curve



The complementary cumulative curve of the damage contains all the information about the output variable considered. Once the risk criteria are defined, it may be used to check if the system fulfils them or not. Figure 3 represents a fictitious case analysis with seven scenarios. The black straight line represents the risk criterion (it divides the damage – probability space in two regions: the region of acceptable risk and the region of unacceptable risk).

Risk Evaluation in the literature

All three Baltic State Risk Assessments provide risk matrices (3x3 or 4x4) that establish consequences and likelihoods on a qualitative scale. The ARA report, in addition to providing a 5x3 risk matrix, also evaluates risk on the basis of histograms and risk summaries.

Poyry (2010a,b), Oxera (2007), CBP (2006) do not use for their final evaluation a risk matrix, as the criteria they adopted are not strictly speaking “risk criteria” (see box on *Risk criteria in the literature*), so they derive their conclusions on the basis of their cost-benefit analyses.

4. Summary

The purpose of this report has been to provide guidance for undertaking a risk assessment as per Article 9 of the Regulation 994/2010. It has presented a brief overview of the main tools and essential features used for performing risk assessments, and has related these tools to the requirements and specificities of the gas system. In doing so, the report has combined general risk management methods with a sector-specific approach. The main steps of the risk assessment have followed best practices, not only through employing ISO standards but also by drawing on substantive risk assessments carried out by industry, academia and policy-makers.

This report enables member states a certain degree of freedom in choosing the optimal methods for assessing risks to their respective gas supplies.

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Annex

- 1. ISO 31000**
- 2. Energy security Indicators**
- 3. A formal extended definition of Risk**
- 4. Techniques for Risks identification**
- 5. Review of FP-7 research projects**
- 6. Classical and Bayesian estimation**
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ANNEX 1

ISO 31000

The ISO 31000 International Standard provides principles and generic guidelines on risk management. This International Standard can be used by any public, private or community enterprise, association, group or individual. Therefore, this International Standard is not specific to any industry or sector. This International Standard can be applied throughout the life of an organization, and to a wide range of activities, including strategies and decisions, operations, processes, functions, projects, products, services and assets. The standard can be applied to any type of risk, whatever its nature, whether having positive or negative consequences.

According to ISO the risk management process should be an integral part of management, embedded in the culture and practices of the organization and tailored to the business processes of the organization. It comprises the following activities:

1. Communication and consultation

Communication and consultation with external and internal stakeholders should take place during all stages of the risk management process. Effective external and internal communication and consultation should take place to ensure that those accountable for implementing the risk management process and stakeholders understand the basis on which decisions are made.

2. Establishing the context

By establishing the context the organization articulates its objectives, defines the external and internal parameters to be taken into account when managing risk and sets the scope and risk criteria for the remaining process.

3. Risk assessment

Risk assessment is the overall process of risk identification, risk analysis and risk evaluation. (ISO /IEC 31010 provides guidance on risk assessment techniques)

4. Risk treatment

Risk treatment involves selecting one or more options for modifying risk, and implementing those options. Risk treatment options are not necessarily mutually exclusive or appropriate in all circumstances. The options can include e.g.: avoiding the risk, removing the risk source, changing likelihood, changing consequences, sharing the risk with another party or parties.

5. Monitoring and review

Both monitoring and review should be a planned part of the risk management process and involve regular checking or surveillance. The organization's monitoring and review process should encompass all aspects of the risk management process for the purpose of ensuring that controls are effective and efficient; obtaining further information to improve risk assessment; analyzing and learning lessons from events; detecting changes in the external and internal context, including changes to risk criteria and the risk itself; identifying emerging risks.

The risk management process is presented in Figure 1:

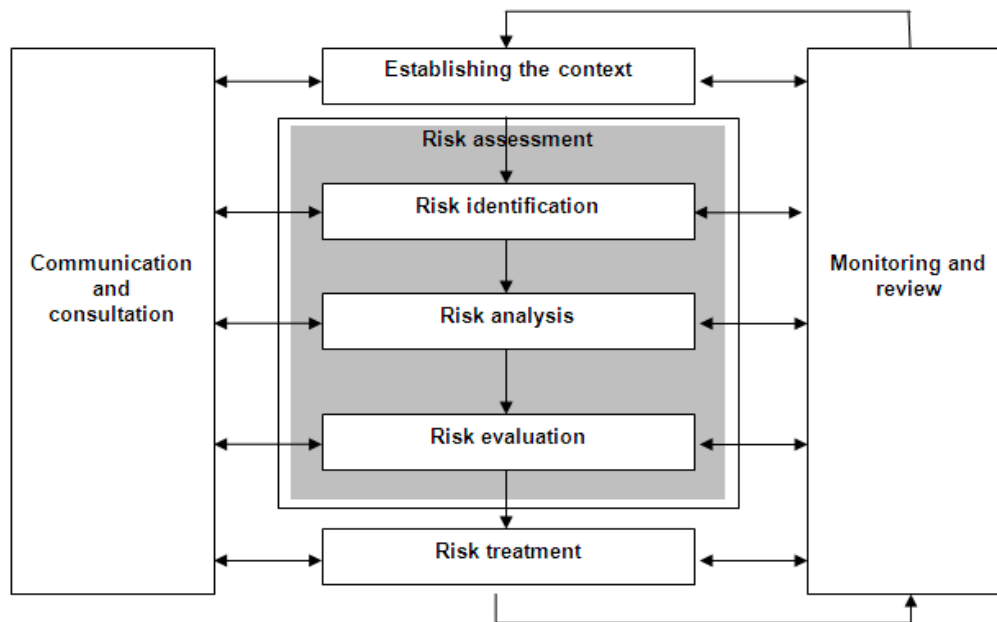


Figure 1: Risk management process

Reference

ISO 31000:2009, Risk management – Principles and guidelines

ISO/IEC 31010, Risk management – Risk assessment techniques

ANNEX 2

Energy Security Indicators

1. Macro-economical indicators

a) Energy intensity: The energy intensity of GDP is the ratio of primary energy consumption expressed in tons of oil equivalent (toe) to GDP (expressed in euro).

b) Gas consumption per capita

c) Net gas imports bill: Vulnerability is not only linked to dependency on imports expressed in quantities, but also to the value of these imports. The net gas import bill takes into account the net imports and the average annual gas prices.

d) Average gas prices: This indicator compares the gas prices and volatility of prices among MS.

2. Energy balance indicators

These indicators are used to compute the energy balance of the total national market, including imports, exports, the transformation sector, the energy industry use, distribution losses and conversion losses, non-energy use and final consumption indicators.

3. Reserves indicators

The reserves-to-production ratios (R/P ratios) indicate the years of production left at current production levels. It has to be noted that neither reserves nor production are fixed. Consequently, a combination of these factors will also be a dynamic quantity.

An alternative indicator is a reserves-to-consumption ratio, which expresses the proven reserves of a country in terms of years of actual gas consumption.

4. Sectoral indicators

The fourth group of indicators quantifies the relative gas consumption of the various sectors. Given the sectoral differences between MS, a gas disruption will have different impacts on their economies. An example would be the share of gas-fired power generation in total industrial electricity consumption.

These figures imply different needs for seasonal flexibility, different peaks of gas demand, different possibilities for interruptible contracts and fuel substitution and fundamentally, different level of importance attached to security of gas supply.

5. Diversification indicators

Diversification is regularly regarded as the main solution to energy insecurity. However, diversification is a very broad and general concept. We try to assess diversification based on six simple sub-indicators for diversification.

a) Diversification of primary energy mix: The first of six sub-indicators is the diversification indicator of the primary energy mix (PEM). The gas shares of the PEM of all MS are compared over the years.

b) Diversification of electricity production: A second diversity aspect is the diversification of the electricity production. In the context of the Regulation, gas shares used for power generation between countries can be compared. These indicators are interesting to analyze spill-over effects on the electricity sector in the event of a gas disruption.

c) Diversification of gas suppliers: A third important element in this respect is the diversification of the supplier portfolio of each Member State.

d) Diversification supply routes: Another important consideration is the number of entry points for imported fuels.

e) LNG diversification: Another way to look at diversification is LNG diversification. If a country has access to both natural gas by pipeline and gas in the form of LNG by transport over sea, it can be considered as more diversified. The evolution of pipeline and LNG shares can be an useful indication of how countries are diversified with regard to LNG.

6. Import risk indicators

The import risk indicators are trying to quantify a certain risk involved with natural gas and LNG imports for every MS, using supplier country risks and transit country risks. We are currently using OECD-country risks, but want to construct our own country risks for the main transit and supplier countries. Market concentration and import (inter)dependency are discussed.

a) Market concentration: A useful index for determining import risk can be borrowed from economics: the *Herfindahl-Hirschman Index* (HHI), which provides a measure of market concentration. In the energy sector, this index has been used to determine a country's level of supply diversification (by calculating the sum of the squared market shares of each supplier for a given country).

$$H = \sum_{i=1}^N s_i^2$$

where s_i is the market share of firm i in the market, and N is the number of firms. This can also be extended to consider risk associated to the gas exporting country (for example by referring to OECD country risk ratings). Here, the indicator for market concentration for gas import would be expressed as such:

$$c_i = \frac{\sum_{j=1}^N r_j sh_{ij}^2}{\sum_{j=1}^N r_j}$$

where

N is the number of gas exporting countries (suppliers)

r_j is the risk associated to the gas exporting country (supplier) j

sh_{ij} is the share, in the total import of gas, of gas coming from supplier j

(if all the risks are equal, the smaller the value of c , the more concentrated is the market, i.e. the less suppliers). The final value of the market concentration index for gas import is

$$IC_i = 1 - \frac{c_i - \min_i(c_i)}{\max_i(c_i) - \min_i(c_i)}$$

The larger the value, the less the import risk.

A similar measure found in biology, the *Shannon–Wiener index*, has also been used to determine diversity not only in imports but also in relation to the level of fuel mix diversification, using the formula:

$$I_{Shannon} = \frac{-1}{\log N} \sum_n p_n \log(p_n)$$

where N is the total number of energy sources in the PEM and p_n is the share for each source. The maximum value of the index is 1 and is reached when all the shares are equals to $1/N$; the minimum value is 0 and is reached when one of the shares is equal to 1 and the rest to 0. The larger the index, the more diversified the country and we assume that it is more “secure”.

b) Import dependency: Import dependency can be expressed as import over total gas consumption:

$$ID_i = \frac{Gas_import_i}{GIC_gas_i}, \text{ for every } i = 1, \dots, n_{MS} \text{ (GIC stands for Gross Inland Consumption). This}$$

quantity is negative for exporting countries.

Next to the computation of traditional import dependency indicators (based on annual data), it can also be useful to compute simple indicators for *seasonal import dependency*. Seasonal fluctuations in gas demand in all countries are exceptionally high. Since domestic production (if any) has a rather flat (constant) profile throughout the year, import dependence during periods of high demand becomes much more significant.

7. Infrastructure indicators

a) Storage infrastructure

Storage infrastructure is mainly needed to meet seasonal fluctuations of gas demand.

$$IS_i = \frac{Gas_storage_capacity_i}{Final_gas_consumption_i}$$

This indicator has a dimension, because the 2 quantities, gas storage capacity and final gas consumption have different units. An indicator also needs to account for seasonal variation in storage and be wary of temporal/unit measurements (peak, average, daily, etc) as well as the type of storage (principally base/peak load).

b) Interconnection infrastructure

Interconnection indicators need to take into account the number of entry/exit points and the maximal technical capacity of each (in relation to actual flows). What also matters is the length and reserved capacity of the supplying pipeline before it enters the national gas market.

c) LNG Infrastructure

Some European countries have the ability to acquire additional LNG shipments through their existing LNG-terminals. An indicator could take into account the total maximal import capacity of LNG facilities in relation to current usage (as well as any cross-border commitments to withdraw/offer LNG)

d) Infrastructure Standard⁴⁰ (994/2010)

Definition of the N-1 formula: The N-1 formula describes the ability of the technical capacity of the gas infrastructure to satisfy total gas demand in the calculated area in the event of disruption of the single largest gas infrastructure during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years. Gas infrastructure includes the gas transmission network including interconnectors as well as production, LNG and storage facilities connected to the calculated area. The technical capacity of all remaining available gas infrastructure in the event of disruption of the single largest gas infrastructure should be at least equal to the sum of the total daily gas demand of the calculated area during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years. The results of the N-1 formula, as calculated below, should at least equal 100 %.

a. Calculation method of the N-1 formula:

$$N-1[\%] = \frac{EP_m + P_m + S_m + LNG_m - I_m}{D_{max}} \times 100, N-1 \geq 100\%$$

b. Calculation method of the N-1 formula using demand-side measures:

The N-1 shall also be considered fulfilled where it is demonstrated in the Preventive Action Plan that a supply disruption may be sufficiently compensated for, in a timely manner, by

⁴⁰ Annex 1 regulation

appropriate market-based demand-side measures. For that purpose, the formula provided in point 4 of Annex 1 of the Regulation shall be used.

$$N-1[\%] = \frac{EP_m + P_m + S_m + LNG_m - I_m}{D_{max} - D_{eff}} \times 100, N-1 \geq 100\%$$

"D_{eff}" means the part (in mcm/d) of D_{max} that in case of a supply disruption can be sufficiently and timely covered with market-based demand-side measures in accordance with Article 5(1)(b) and Article 6 (2) of the regulation.

e) Supply standard⁴¹ (994/2010)

The Supply Standard stipulates that gas supply needs to be ensured for protected customers in the three following cases:

- a) extreme temperatures during a seven-day peak period,
- b) any period of at least 30 days of exceptionally high gas demand, and
- c) for a period of at least 30 days in the case of the n-1 scenario during average winter conditions.

Formally these three cases are scenarios. The Regulation does not require to estimate their respective probabilities.

⁴¹ Article 8, EC Regulation 994/2010

ANNEX 3

A formal extended definition of Risk

The definition of Risk given in section 3.2 of the main text in this document is a simplification of the full definition needed to address such a concept including all uncertainties that may arise in a system. The basic idea remains the same: Risk is adequately addressed by answering formally to the following questions:

- What can happen and why?
- What are the consequences?
- What is the probability of its future occurrence?

Kaplan and Garrick (1981) showed that a formal answer to these three questions requires describing risk through the use of a set of triplets

$$R = \{ \langle s_i, p_i(\phi_i), f_i(y_i) \rangle \} \quad i = 1, 2, \dots, N, \quad (1)$$

where

4. s_i represents scenario i in the set of n scenarios considered.
5. $p_i(\phi_i)$ is the probability density function (pdf) that characterises our state of uncertainty about scenario i .
6. $f_i(y_i)$ is the pdf that characterises our uncertainty about the potential consequences induced by our uncertainty about the system parameters under the conditions of scenario i .

This constitutes a formal mathematical definition of risk. Using this scheme to address the concept of risk means a full acknowledgement of all the uncertainties affecting the system under study.

It means that all possible scenarios must be identified and the uncertainty about their potential occurrence must be assessed (realise the difference with the text in the main document, ϕ_i is replaced by $p_i(\phi_i)$); not only the probability of each one must be estimated, but the pdf that characterises the uncertainty about the whole set of probabilities: the multivariate pdf that characterises the uncertainty about the complete set of scenarios, subject to the restriction that the addition of all probabilities is one (although in principle the dimension of the probability space considered is N – the number of scenarios considered – the actual dimension of the space is $N-1$).

Moreover, for each scenario, the uncertainties associated to each potential consequence, in terms of pdf, must also be estimated (realise the difference with the text in the main document, y_i is replaced by $f_i(y_i)$). In many scenarios the boundary conditions and the values of many system parameters are not well known. An adequate estimation of consequences demands a proper estimation of input uncertainties and the propagation of uncertainties through the system model (most likely via Monte Carlo).

Intermediate possibilities between the approach adopted in the main text and the approach shown until now in this annex are possible. The most frequent one consist in ignoring the uncertainty in the assessment of probabilities of occurrence of different scenarios but acknowledging the uncertainty in possible outcomes of a given scenario.

ANNEX 4

Techniques for Risk identification

Several risk identification techniques exist in the literature. IEC/ISO 31010 provides a detailed overview and a comparison of these techniques. Some of the most widely used risk identification techniques are:

- f) brainstorming
- g) structured or semi structured interviews
- h) check lists
- i) Hazard and operability analysis (HAZOP)
- j) Failure mode and effects analysis (FMEA)

This Annex provides a short description of each technique, highlighting main characteristics, when they are most useful, types of inputs needed and outputs obtainable, most remarkable strengths and limitations.

a) Brainstorming

Brainstorming involves stimulating and encouraging free flow conversation amongst group of knowledgeable people to identify potential failures modes and associate hazards, risks, criteria for decisions.

Use: Brainstorming places heavy emphasis on imagination and is therefore particularly useful when identifying risks of new technology, where there is no data or where novel solutions to problems are needed.

Input: Team of people with knowledge of the system under analysis.

Output: Might be a list of risks and current controls

Strengths: encourages imagination (novel situation and new risks); involves key stakeholders; relatively quick and easy

Limitations: it is relatively unstructured, it may not have been comprehensive; participants may lack the appropriate knowledge; group dynamics.

b) Structured and semi structured interview

Individuals are asked a set of predefined questions which encourage the interviewee to view situations from different perspective. See

Use: They can be useful where it is difficult to get people together for a brainstorming session.

Input: A clear definition of the objectives of the interviews, a list of interviewees, a prepared set of questions.

Output: Stakeholders views on the issues which are the subject of the interviews.

Strengths: allow people time for considered thought about an issue; more in depth consideration of an issue in a one to one communication; enable the involvement of a large number of stakeholders than brainstorming.

Limitations: time consuming; the triggering of imagination may not be achieved.

c) Check lists

They are list of hazards, risks or control failures that have been developed usually from experience (as results of previous risk assessment or past failures)

Use: They may be used as part of other risk assessment techniques, but are most useful when applied to check that everything has been covered after a more imaginative technique.

Inputs: Prior information and expertise on the issue.

Outputs: They may be a list of controls which are inadequate or a list of risks.

Strengths: may be used by non experts; combine wide ranging expertise into an easy to use system; help ensuring that common problems are not forgotten.

Limitations: address the known known's; encourage tick the box type of behaviour; tend to be observation based, so miss problems that are not readily seen.

d) Hazard and Operability Analysis (HAZOP)

The HAZOP study method is the most widely known technique for hazard identification. It was developed by ICI in the 1960s and its use and development was encouraged by the Chemical Industries Association guide published in 1977.

The concept of Hazard study first appeared with the aim of identifying possible hazards present in facilities that manage highly hazardous materials. The purpose was to eliminate any source leading to major accidents, namely toxic releases, explosions and fires (Seveso Directive). However, over the years, Hazop's application extended to other types of facilities because of its success in identifying not only hazards, but also operational or organizational problems. Hazop has been adopted for medical diagnosis systems, road-safety measures, identification of managerial and organizational failures, black out analysis, among the others. This diversity of usages illustrates how Hazop has become considered as a powerful technique to improve many kinds of systems.

It is a highly disciplined procedure meant to identify how a process may deviate from its design intent. It is defined as the application of a formal, systemic critical examination of the process and the engineering intention of new or existing facilities to assess the potential for malfunctioning of individuals pieces of equipment. It is a technique that "provides the opportunities for people to let their imagination go free and think of all possible ways in which hazards or operating problems might arise, but – to reduce the chance that something is

missed- it is done in a systematic way. The study is carried out by a team so that the members can stimulate each other and build upon each other's ideas" (HAZOP and HAZAN, *Identifying and assessing process industry hazards*, Trevor Kletz, 1992).

The HAZOP process is a qualitative technique based on the use of guide-words which question how the design intention or operating conditions may not be achieved at each step of the design, process, procedure or system. It is carried out by multidisciplinary team.

Inputs: essential inputs are current information about the system, process or procedure to be reviewed. Inputs may include: drawings, specification sheets, flow sheets, process control and logic diagrams, layout drawings, operating and maintenance procedures, and emergency response procedures.

Steps in HAZOP study:

- nomination of a HAZOP leader
- definition of the objectives and scope of the study
- establishing a set of key or guidewords for the study,
- defining a HAZOP team; usually the team is a multidisciplinary team and should include design and operation personnel with appropriate technical expertise to evaluate the effects of deviations.
- collection of the required documentation
- splitting the system, process or procedure in smaller elements or sub systems
- for each items in the sub-system apply the guidewords one after the other to postulate possible deviations which will have undesirable consequences
- where undesirable outcomes are identified, agreeing the cause and consequences in each case and suggesting how they might be treated to prevent them occurring
- documenting the discussion

Outputs: minutes of the HAZOP meeting with items for each review point recorded. This should include: the guide word used, the deviation, possible causes, actions to address the identified problems and person responsible for the action.

Strengths: systematic and thorough examination of a system, process or procedure; it involves a multidisciplinary team; it is applicable to a wide range of systems, processes and procedures; it creates a written record of the process of risk identification

Limitations: a detailed analysis can be time consuming and expensive; a detailed analysis requires a high level of documentation; it can focus the discussion on detail issues of design and not on wider external issues

d) Failure mode and effects analysis (FMEA)

Failure modes and effects analysis is a technique used to identify the ways in which components, systems or processes can fail to fulfil their design intent.

FMEA identifies:

- all the potential failure modes of the various parts of a system
- the effects these failures may have on a system
- the mechanisms of failure
- how to avoid the failure

Use: there are several applications of FMEA: design, system, process, service.

Inputs: FMEA needs information about the elements of the system in sufficient detail for meaningful analysis of the ways in which each element can fail.

Outputs: The primary output of FMEA is a list of failure modes, the failure mechanisms and effects for each component or step of a system or process.

Strengths: widely applicable to human, equipment and system failure modes; identify components failure modes, their causes and their effects on the system; identify single points failure modes and requirement for redundancy or safety systems.

Limitations: it can only be used to identify single failure modes; it can be time consuming and costly; it can be difficult and tedious for multi-layered systems.

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ANNEX 5

Review of FP-7 research projects

In this Annex we present an overview of existing FP7 projects which are related to risk assessments, vulnerability and security in the energy world. The following FP7 projects are discussed: EURACOM, INTEGRISK, SECURE, REACCESS, COUNTERACT

EURACOM: European Risk Assessment and Contingency planning Methodologies for interconnected energy networks

EURACOM- European Risk Assessment and Contingency planning Methodologies, is an EC-FP7 financed Coordination Action. EURACOM addresses the issue of protection and resilience of energy supply for European Interconnected energy networks. The main goal of EURACOM is to identify, together with European Critical Energy Infrastructure operators, a common and holistic approach for risk assessment and contingency planning methods. This objective to increase resilience with respect to network dependencies in energy infrastructures is facilitated by developing common methodologies and tools that assure a dialogue, sharing of data and close co-operation between energy operators, large energy users, security solution suppliers, administrations, regulatory bodies, and other stakeholders. This approach requires common methodologies all along the value chain, from production to distribution. It also requires common methodologies at different hierarchical levels, from individual companies up to European level. By establishing coherent risk management procedures across energy sectors and EU countries, the resilience of critical energy services across the whole ('end-to-end') energy infrastructure chain is sought to be increased. This is why the EURACOM method is applicable to various energy sectors and at various levels within those sectors.

EURACOM covers all applicable hazards to the energy sector, including threats from natural causes, human intent, technical failure, human failure, dependencies of other Critical Infrastructures and other dependencies. Furthermore the method includes both risk assessment and contingency planning.

The EURACOM methodology relies on an integrated and holistic approach to risk management and contingency planning. It aims to support energy infrastructure operators to adapt to a changing landscape and new challenges as given by the adoption of the European Energy Directive. It enables operators to improve their risk management practices and to implement their own holistic risk management system building on and integrating with existing practices and systems (e.g. asset management). For the above mentioned reasons, the method has been conceived to be simple, flexible and modular. Moreover it provides guidance on the basis of essential steps and elements and on the tailoring for the application of the method in specific energy sub sectors (electricity, oil, gas).

Objective: to identify a common and holistic approach (end-to-end energy supply chain) for risk assessment and contingency planning.

Domain: Energy: gas, oil, electricity

Main concepts used: *Risk Assessment* is the initial process used to assess the potential impact and the likelihood of threats exploiting vulnerabilities in order to provide a risk rating prior to the implementation of any risk treatment or mitigation

Scope and Variables:

- Scope of the report is to concentrate on energy operators – e.g. *not* the policy-makers or regulators/associations but the actors in the supply chain: producers, TSO/DSO, suppliers, consumers, etc.
- In the case study of gas, EURACOM *narrow the scope* to transmission, which is justified “by the fact that energy grids are the pivotal point of dependencies and cascading effects at European scale whether we talk about dependencies between grids themselves or their interaction with source and distribution.”
- Variables: *Primary Gas Transmission Infrastructure*: Pipes, storage tanks, and compressors; *Supporting Gas Transmission Infrastructure*: gas receipt station, odourisation, blending station, SCADA/Telemetry, ICT, facilities, engineering functions, maintenance functions, and tools for contingency plans; *Dependencies*: Tankers, Terminals, Interconnectors, PIG launchers (see pg. 55)

Methodology and Framework

The seven steps of the EURACOM risk assessment process are summarized below (high level perspective):

1. Set up of an holistic team with an holistic view
2. Define the holistic scope of the risk assessment
3. Define the risk assessment scale (probability and impact)
4. Understand the assets in the scope
5. Understand the threats context
6. Review security and identify vulnerabilities
7. Evaluate and rank the risks

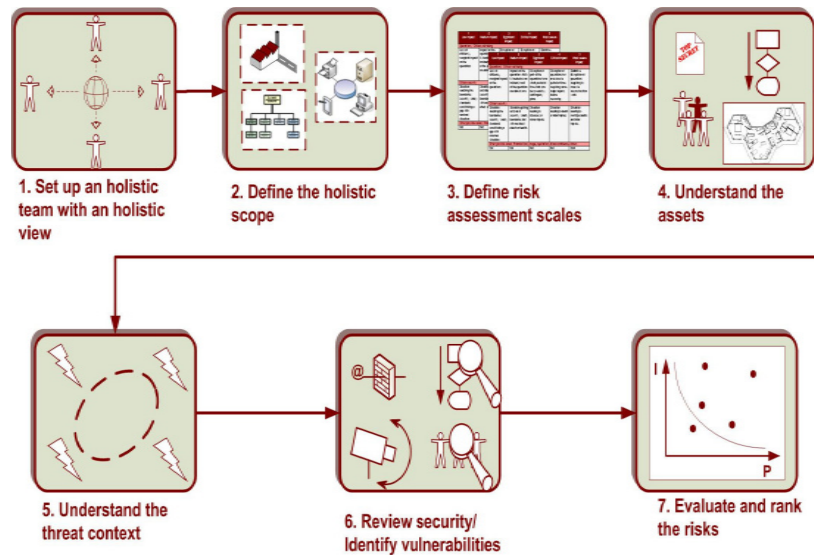


Figure 1: the EURACOM risk assessment approach

This is called holistic risk management, which considers 4 dimensions – physical security / information and communication technology security / organisational security / human factors regarding security. These 4 dimensions are used to analyse each of the components of the risk – e.g. assets, vulnerabilities, threats and effects.

Outcome: Only the step-by-step process of risk identification and assessment is covered. The example of assessing risks in gas transmission provides only a very general summary of possible risk factors. There is no concrete empirical case study, and therefore no discussion of results of the risk assessment.

Evaluation: The narrowed scope means that risks emanating from a different part of the supply chain are unaccounted for, even though they may affect the transmission grid (for example, the risks involved in cross-border energy dependence are not mentioned)

- there are no concrete outlines for identifying specific risks and vulnerabilities in the gas transmission system.

- too general to be of much use – e.g. concretely applying the step-by-step process encounters the risk of omitting several important variables.

- moreover, there are several variables not taken into account, perhaps because they are outside of the scope but nevertheless impact on the risks to transmission (e.g. capacity of gas storage – if you’ve got enough gas stored then the consequences of a destroyed interconnector are less severe – but maybe that’s accounted for in contingency planning?)

SECURE: Security of energy considering its uncertainty, risk and economic implications

The SECURE project builds a comprehensive framework that considers all the issues related to the topic of security of supply, including geopolitics, price formation and the economic and technical design of energy markets inside and outside the EU. Tools, methods and models are developed to measure and assess EU security of energy supply both outside the EU and inside the EU.

The objective is to evaluate the vulnerability of the EU to the different risks which affect energy supplies in order to help optimizing the Union's energy insecurity mitigation strategies, including infrastructure investment, demand side management and dialogue with producing countries. This project will develop energy security indicators for all the major energy sources in order to identify the *risk* factors and quantify the EU exposure to volume and price risks in the short and long terms, including impacts of severe accidents and terrorist threats.

Costs and benefits (both measurable and perceived) of energy security will be evaluated for different energy supply/demand scenarios to help policy makers providing the most appropriate institutional, political and industrial solutions. All major energy sources and technologies (oil, natural gas, coal, nuclear, renewables and electricity) will be addressed from upstream to downstream with both a global and sectoral analysis studying in depth issues such as technical, economic/regulatory and geopolitical risks.

The analysis will also integrate demand as a key issue related to energy security. The SECURE project has both a strong quantitative and qualitative component and will at the end not only provide a comprehensive methodological and quantitative framework to measure energy security of supply, but it will also propose policy recommendations on how to improve energy security taking into account costs, benefits and risks of various policy choices.

A. Risk analysis-based measures of energy security

Type: Deliverable No 1.2 for the FP7 Project (Security of Energy Considering its Uncertainty, Risk and Economic Implications - SECURE)

Objective: providing an overview of the different methods used to assess energy security risks from different viewpoints.

Domain: energy / all

Main concepts used: In the context of security, 'risk' is defined as a function of three variables: 'threat' is the measure that a specific accidental or intentional event will take place. 'Vulnerability' is the measure of likelihood that various types of safeguards fail. 'Consequence' is the magnitude of negative effects in case of an accident or successful attack. Risk is a kind of quantifiable 'incertitude' (in contrast to the unquantifiable incertitudes of uncertainty and ignorance).

Scope and Variables: There are three types of risks (according to Stern 2002) in the gas sector: investment and facility risks, exporters' reliability risks and transit risks. The Secure project adds liberalisation as a potential source of risk, and points to contingency tools such as storage and supply flexibility.

Methodology and Framework: the study is interested in comparative risk assessment, an expected utility approach, a Bayesian and scenario-based approach, and particularly multi-criteria analysis.

Outcome: Multi-Criteria Analysis (MCA) combines a set of technology specific indicator values and stakeholder preferences within an interactive framework.

Evaluation: The discussion of risk evaluation methodologies is not integrated with the discussion that is specific to energy security. Therefore this deliverable only provides a generic overview of risk assessment methodologies.

B. Natural Gas Dependency and Analysis of Economic, Physical, and Social Impact of Natural Gas Supply Disruption

Type: Deliverable No 5.2.1 for the FP7 Project (Security of Energy Considering its Uncertainty, Risk and Economic Implications - SECURE)

Objective: examine the gas demand of the EU and categorize events that may give rise to physical natural gas supply shocks

Domain: gas / EU

Main concepts used: *vulnerability* is the exposure to a disruption and the extent to which the energy sector will experience adverse effect (harm or damage) from that disruption. Vulnerability of a country to energy supply disruptions is time dependent and multidimensional. Therefore, although it is a function of risk and resilience (robustness or the speed of recovery) it depends on a complex set of inherent states and hence can be represented through multiple metrics such as (strength and capability, i.e., ability and capacity) of a country to anticipate, cope with, resist and recover from the impact of such a disruption. In this sense, the degree of vulnerability is a combination of different factors; among which is energy intensity, flexibility in modifying the energy mix, quick response and adaptation to energy price increases and the ability to manage disruption of the energy supply. *Threat* is the intent and capability to cause adverse effects. *Risk* is a measure of the probability of a supply disruption occurring, and severity of adverse effects that could result. Risk can be interpreted as result of a threat. Both threat and risk require knowledge about vulnerability.

Scope and Variables: Six main categories of potential risks to natural gas security – technical, geopolitical, regulatory, economic/commercial, environmental and transit risks. Risk assessment and risk management can be pursued only after full knowledge on vulnerability is accumulated. In risk assessment, the analyst often attempts to answer the following set of questions: What can go wrong? What is the likelihood that it would go wrong? What is exposed to harm or damage? What is the frequency of endangerment? How often it can happen? And, what are the consequences? These questions allow one to identify, measure, quantify, and evaluate risks and their consequences and impacts.

Methodology and Framework: Main goal of the ‘risk assessment’ phase of the report is to investigate options for mitigating gas supply disruptions (p 30). These are categorised as ‘flexibility of supply’; ‘flexibility of demand’; flexibility of infrastructure’ – sub-categorised as storage, diversification, interconnections, and EU policies; ‘cooperation with supplier and transit countries. From there it discusses extensively the impact of the January 2009 gas crisis on member states.

Outcome: offers a generic set of conclusions about the need for more coordination, investment, regulation, solidarity, flexibility and emergency response mechanisms. No actual risk assessment is performed, rather, only the relevant variables are introduced.

Evaluation: The ‘mitigation options’ section (from p. 30) provides a useful way of establishing the context for the EC Gas Supply Regulation Risk Assessment.

REACCESS: Risk of energy availability: common corridors for Europe supply security

The REACCESS project aims at analysing present policies concerning EU MS and Community targets for energy import. Evaluating technical, economical and environmental characteristics of present and future energy corridors within Europe and among Europe and the supplying regions of the World, taking into account the different typology of infrastructures and technologies (railways, pipelines, cables, terminals, ships and other carriers, ..), the flows and the distances involved for oil, natural gas, coal, electricity, uranium, biomass and hydrogen (reference to the work done within the ENCOURAGED Project and other research activities).

Introducing suitable parameters and indicators (including technical and socio-economical reliability) and cost components (investment, O&M, externalities) incorporating the above mentioned information, which may help a global evaluation of supply options (energy vectors, infrastructures, origins of the sources) and their impacts on economy, society, energy and environment toward sustainability. Identifying main corridors for primary and secondary energy carriers to EU27+ Implementing these energy corridors into an adapted version of the pan-EU TIMES model (PEM) built in the framework of the NEEDS IP or into other modelling tools.

Analysing scenarios, in which for the fulfilment of the EU27+ energy needs, the import strategies of primary (and secondary) energy carriers compete with the evolution of energy efficiency policies (i.e. white certificates for the energy saving), the introduction of new energy schemes and the development of renewables, in the framework of the EU environmental targets for 2030-2050. Some hypotheses related to the energy supply and demand strategies of regions outside of Europe will be also assumed, given their potential impacts on the international energy prices (e.g. China, India, OPEC, Russia etc.)

Risks on Energy Security of Supply: an exploratory analysis for the researcher⁴²

Type: FP7 Project – Risks of Energy Availability; Common Corridors for Europe Supply Security, 1st Conference proceedings (Athens)

Objective: to underline the importance of risk analysis and minimization in addressing the overall energy supply status of the EU.

Domain: European Union, oil and gas

Main concepts used: Risk analysis (e.g. categorisation of the ‘most important risks’ to energy supply)

Scope and Variables: assesses/evaluates energy supply security by interpreting historical data.

Methodology and Framework: Categorises and then reviews seven types of risks based on their past frequencies and consequences. These are:

1. Conflicts (war)

⁴² Chapter 2 (Flouri, Karakosta, Douka, Flamos)

2. Political instability (regime change, protests, revolutions)
3. Terrorist attacks
4. Export restriction (embargoes)
5. Accidents (explosions, leaks, any unintentional interruptions)
6. Weather conditions (hurricanes, earthquakes, etc)
7. Monopolistic Practices (cartelisation, etc.)

The study applies a qualitative assessment of the probability and impact of these related risks.

Outcome: The study concludes that, for natural gas, the probability of Risks 1-4 are low, for Risks 5-6 medium, and for Risk 7 is high. On the impact side, Risks 1-2-7 are high, Risks 4 and 5 are medium, and Risks 3 and 6 are low.

Evaluation: Only does a brief, ad-hoc analysis of past events. Doesn't mention anything about the resilience of the system or how to calculate/mitigate future risks. For all its introductory remarks about the need for method to analyse risk, ultimately it provides a slapdash, half-baked one.

COUNTERACT: Cluster Of User Networks in Transport and Energy Relating to Anti-terrorist Activities

Critical infrastructures are those which, if disrupted as a result of a *terrorist* attack, would have an impact of regional, national or international scale on communities and economies. Such an attack could be co-ordinated, disrupting several infrastructures directly or through cascade effects. COUNTERACT assesses and recommends feasible and cost-effective solutions for the improvement of security in four key sectors of critical infrastructure: urban public transport, rail transport, air transport, maritime transport, freight transport and energy. These sectors have been grouped in different clusters: Surface Passenger Transport - Freight Transport - Air Transport – Energy.

The Counteract energy cluster has provided interesting deliverables:

Estimated Recovery Times for Energy Infrastructures Damaged by Terrorist Attacks

This study aims at the identification of the duration of critical infrastructure component outages after being struck by a terrorist attack. Measures to recover the infrastructure and the supply of energy currently in place are analyzed and evaluated to identify where improvements are possible. Historically such attacks have taken place within and outside Europe, but the impacts were limited. An overview of the natural gas, oil, and electricity systems furthermore gave indications that measures to respond to technical failures or weather hazards together with spares for maintenance purposes would be sufficient to quickly repair any damage pipelines, pylons, or transformers. Applying scenarios reveal that the energy that is lost due to single point disruptions like terrorist attacks can be replaced immediately. Recovery times of the infrastructure components ranged from 3 months to over 3 years depending on the component and the availability of replacement parts. The study recommends taking steps ensuring that missing energy from affected infrastructure components due to disruptions can be supplied via alternatives over a prolonged period of time and to enhance the national and EU wide management of energy crisis situations.

Energy Supply Chain Threat Assessment and Generic Security Guidance

This study presents a risk based approach and an operational model to security management. It gives an overview and an assessment of the terrorist threat to the energy supply chain. The study is designed to allow operators as well as regulators to develop a rational and cost effective protection strategy that will secure assets in accordance with threat levels. For the asset operators the method provides a solid foundation to establish an overview of the attractiveness of their assets with respect to a perpetrator threat, and to facilitate the communication with security advisors and authorities. Fundamentally, the perpetrator threat against the energy supply chain in Europe has been very low in the past - attacks have not resulted in major damage to the targets, reflecting that the perpetrators behind these attacks are leftist or separatist groups. So far, al-Qaida or al-Qaida inspired global jihadi terrorists have not targeted energy supply chain in Europe. This may reflect that the energy supply chain is not the most suitable venue for staging mass casualty attacks. However, al-Qaida's view on the suitability and legitimacy of targeting energy supply chains is evolving. It seems likely that evolving patterns of energy dependence will have the unintended effect of sustaining and in some cases increase trans-national terrorism. It is reasonable therefore to assume that terrorist interest in such targets may grow in the future. The energy supply chain offer many potentially attractive terrorist targets, when the political context makes such attacks meaningful to terrorist and insurgent groups. The risk based assessment model provided by the study allows the stakeholders to priorities actions, and to decide which risks may be tolerated, and which require action to control them or remove them.

Terrorism and European Energy Security: Assessing the challenge

This study assesses the challenge from terrorism towards the European energy supply infrastructure analyzing the resilience of the infrastructure, targeting patterns worldwide, and incentives behind those patterns. The resilience of the energy infrastructure to uncoordinated malicious attacks is estimated by assessing past major accidents and attacks. Historical data on terrorist attacks on energy infrastructure worldwide are analyzed and terrorist targeting is assessed by reviewing the existing literature. The study finds that the current European energy infrastructure is quite resilient to single-point incidents. In addition, the analysis on targeting data revealed that energy infrastructure is not a preferred target for terrorists in general. Terrorists promoting various political causes have reasons to attach less value to energy infrastructure than to other potential targets. However, terrorists with a nationalist-separatist agenda or possible future groups based on single-issue environmentalist/climate platforms may have greater incentives to strike energy infrastructure targets.

INTEG-RISK: Early recognition, monitoring and *integrated* management of emerging, new technology related risks

iNTeg-Risk is a large-scale integrating project aimed at improving the management of emerging risks in the innovative industry. In particular in the area of "New production – technologies & production networks", security or energy supply and its related emergin risks are considered. The project aims at building a new *risk* management paradigm for emerging risks, which is a set of principles supported by a common language, commonly agreed tools & methods and Key Performance Indicators *integrated* into a single framework.

The project aims at improving early recognition and monitoring of emerging risks, seek to reduce accidents caused by them and decrease reaction times if major accidents involving emerging risks happen. iNTeg-risk will reach its goals by promoting a EU-wide cross-sectorial life-

cycle-based integration across all major disciplines, methods and tools as well as through integration of all relevant stakeholders.

Table 1: Overview table FP6 & FP7 project on risk assessment:

PROJECT	RISK ASSESSMENT				
	CONTEXT	RISK SOURCES	RISK ANALYSIS	RISK EVALUATION	RISK TREATMENT
EURACOM	Energy infrastructures (CIP) oil, gas, electricity	All hazards: accidental (human, technical, natural causes, dependencies) and deliberate (terrorist attacks)	Practical evaluation of risk: $R = P \times C$ Qualitative Probability scale	Risk ranking, qualitative	Combination of risk mitigation, avoidance and acceptance
SECURE	Energy: oil, gas, coal, renewables, nuclear, electricity	Technical, environmental, economic, geopolitical	Evaluation of risk: $R = P \times C$ Qualitative and quantitative	Economic costs of remediation and financial aspects of policies and measures	Threats and impact reduction and costs evaluation
REACCESS	Energy corridors: oil, coal, natural gas, uranium, electricity, hydrogen, biomass	Technical, economical, environmental	Socio political risk analysis (social risk, energy risk, political risk, economic risk) Technological risk analysis (risk for people and environment)	Risk ranking	Mitigation measures for disruption (flexibility of demand, supply, infrastructure)
COUNTERACT	Energy, transport and intermodal freight (CPI)	Terrorist attacks	Assets and threats assessment	N.A.	N.A
INTEGRISK	Security of energy supply as part of innovative industry (new production, technologies & production networks)	Technical, human, communication, governance (Emerging risks)	IRGC Framework	Risk ranking	NO

ANNEX 6

Classical and Bayesian estimation

This annex is dedicated to show the most typical and widely used classical and Bayesian estimation methods. These may be used to estimate scenario probability and to estimate the probability density functions (pdfs) that may be used to characterise the uncertainty about random/uncertain model parameters

Classical inference methods

Classical inference methods are based on the assumption of having a random sample. The target is to determine the PDF that generated the random sample. This process may be divided in three steps:

- Model identification
- Parameter estimation, which is divided in two parts
 - Point estimation
 - Interval estimation
- Diagnosis of the model

Model identification consists in finding the most appropriate probability model (uniform, normal, log-normal, exponential, Weibull, etc.) for the sampled data. This task needs the use of graphic tools such as histograms, in addition to the experience in the field under study. Furthermore experts in the field will often have an idea of the distributions that could best represent the data. This part of the process certainly involves subjective elements.

Once the probability model has been identified, the parameters need to be determined. Most probability models are characterised by a set of parameters (parametric models), as for example the mean, μ , and the standard deviation, σ , in a normal (Gaussian) probability model. Estimation is done via techniques of point estimation. These techniques allow identifying a best choice for those parameters. Identifying best choices does not mean that those are the only acceptable ones; other similar values could also be acceptable. A measure of error or of likely alternatives is also needed. This is provided by *interval estimates*.

The last step consists in checking that the hypotheses considered in the whole process were correct. Three hypotheses are normally used: the type of probability model, the independence between the different observations and the homogeneity of the sample.

In the following pages attention focuses on point estimation (first bullet in step 2).

POINT ESTIMATION

The best-known and most widely used methods are the Maximum Likelihood Method and the Method of Moments. The main shortcoming of all these methods is their requirement of sample sizes to get good quality estimates. In practical situations with real engineering facilities it may be quite difficult to get the required sample size.

Method of moments

Method of Moments is probably the oldest inferential method to estimate the parameters of a PDF. K. Pearson developed the method of moments by the end of 19th century. The idea is quite simple. It consists in taking as an estimator of a parameter its equivalent sample quantity. So, the sample mean is the estimator for the mean, the sample variance is the estimator for the variance and so on.

Maximum Likelihood method

The Maximum Likelihood Method is the most widely used and most powerful estimation method in the classical context. Let us assume that we wish to study a random variable X (representing a parameter affected by uncertainty) of a known distribution function type $f(\mathbf{X}|\theta)$, but of unknown parameter θ . In order to estimate θ we take a random sample $\mathbf{X} = (X_1, X_2, \dots, X_n)$, which is assumed to be a random vector, whose components are independent and identically distributed (iid), so that its joint probability density function is

$$f(\mathbf{X}|\theta) = f(X_1, \dots, X_n|\theta) = \prod_{i=1}^n f(X_i|\theta). \quad (6.1)$$

It is important to notice that, in this expression, under the classical view, before sampling, θ is unknown, but has an assigned value that determines what regions of \mathbf{X} are more likely and what regions are less likely. So, this is a function whose unknowns are \mathbf{X} . This is the meaning before sampling. As soon as the sample is available, \mathbf{X} is known, while θ remains unknown. The objective is to determine what value, among all the possible values of θ , makes the sample actually obtained the most likely one. The problem is hence to find the value of θ for which the function defined in (6.1) attains its maximum value. As it is convenient to look at the problem after getting the sample, expression (6.1) is usually written as

$$L(\theta|\mathbf{X}) = f(\theta|\mathbf{X}) = f(\theta|X_1, \dots, X_n) = \prod_{i=1}^n f(X_i|\theta), \quad (6.2)$$

which means that, after sampling, the probability density function of the sample vector is changed into a function of the unknown parameter θ . 'L' stands for 'Likelihood'. From a practical point of view, the function whose maximum is actually computed is not L , but its logarithm $l(\theta|\mathbf{X})$. Both functions reach a maximum at the same point since the transformation to get one from the other one is a monotonic transformation.

As an example, let $\mathbf{X} = (X_1, X_2, \dots, X_n)$ be a sample of size n of a Gaussian random variable whose variance σ^2 is known. We wish to estimate the mean μ of the random variable under study. Under these circumstances, the likelihood function is

$$L(\mu|\mathbf{X}) = f(\mu|X_1, \dots, X_n) = \prod_{i=1}^n f(\mu|X_i) = (2\pi)^{-n/2} (\sigma^2)^{-n/2} e^{-\frac{1}{2\sigma^2} \sum_{i=1}^n (X_i - \mu)^2}, \quad (6.3)$$

whose logarithm is

$$l(\mu|\mathbf{X}) = \ln(L(\mu|\mathbf{X})) = -\frac{n}{2} \ln(2\pi) - \frac{n}{2} \ln(\sigma^2) - \frac{1}{2} \sum_{i=1}^n \left(\frac{X_i - \mu}{\sigma} \right)^2. \quad (6.4)$$

In order to compute the value of μ for which this expression reaches a maximum, we compute its first derivative with respect to μ

$$\frac{\partial l(\mu|\mathbf{X})}{\partial \mu} = -\sum_{i=1}^n \left(-\frac{1}{\sigma} \right) \left(\frac{X_i - \mu}{\sigma} \right). \quad (6.5)$$

The maximum is obtained when this expression equals zero, which happens for the value

$$\hat{\mu} = \overline{X_n} = \frac{1}{n} \sum_{i=1}^n X_i. \quad (6.6)$$

The reader may check, by computing the second derivative that, indeed, the likelihood function reaches a maximum when $\mu = \hat{\mu}$ (second derivative is less than zero when $\mu = \hat{\mu}$). The method may also be applied when a PDF is defined through a vector of parameters; in that case the usual rules for maximizing a multi-parameter function must be applied (to equal first partial derivatives to zero and to check conditions imposed on the Hessian matrix evaluated at the point where first partial derivatives are zero). The method provides a single value as an estimate. If needed, a confidence interval with the desired degree of confidence, may be obtained using interval estimation theory.

The maximum likelihood method has several properties that makes it the most widely used estimation method Mood et al. (1974):

- The estimators obtained through this method are asymptotically unbiased (the limits of their expected values when the sample size tends to infinite are the true values of the parameters).
- They are asymptotically normal since their distributions become normal when the sample size tends to infinite.
- They are asymptotically efficient; for large sample sizes, they are the most accurate estimators.
- They are sufficient since they summarise all the relevant information contained in the sample.
- They are invariant; if $\hat{\theta}$ is the maximum likelihood estimator of θ , and $\theta' = f(\theta)$, then $f(\hat{\theta})$ is the maximum likelihood estimator of θ' .
- Table 6.1 provide a summary of most used probability laws. The binomial, poisson, exponential and gamma distributions are the most suitable ones for estimating scenario probabilities.

Table 6.1.- The most useful probability distributions functions, their parameters and their maximum likelihood estimators.

• Distrib ution	• PDF	• Paramet ers	• Estimators
• Unifor m	$\frac{1}{b-a}; a \leq x \leq b$ <ul style="list-style-type: none"> • $0; \text{otherwise}$ 	<ul style="list-style-type: none"> • a: Minimum • b: Maximum 	$\hat{a} = \min\{x_1, \dots, x_n\}$ <ul style="list-style-type: none"> • $\hat{b} = \max\{x_1, \dots, x_n\}$
• Log- uniform	$\frac{1}{x \ln(b/a)}; a \leq x \leq b$ <ul style="list-style-type: none"> • $0; \text{otherwise}$ 	<ul style="list-style-type: none"> • a: Minimum • b: Maximum 	$\hat{a} = \min\{x_1, \dots, x_n\}$ <ul style="list-style-type: none"> • $\hat{b} = \max\{x_1, \dots, x_n\}$
• Norma l	$\frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]$ <ul style="list-style-type: none"> • $\sigma > 0$ 	<ul style="list-style-type: none"> • μ: mean • σ^2: variance 	$\hat{\mu} = \bar{x}_n = \frac{1}{n} \sum_{i=1}^n x_i$ <ul style="list-style-type: none"> • $\hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x}_n)^2$ •
• Log- normal	$\frac{1}{x\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{\ln x}{\sigma}\right)^2\right]$ <ul style="list-style-type: none"> • $x > 0, \sigma > 0$ 	<ul style="list-style-type: none"> • μ: mean of $\ln(x)$ • σ^2: variance of $\ln(x)$. 	$\hat{\mu} = \bar{x}_n = \frac{1}{n} \sum_{i=1}^n \ln x_i$ <ul style="list-style-type: none"> • $\hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^n (\ln x_i - \bar{x}_n)^2$
• Expon ential	<ul style="list-style-type: none"> • $\lambda e^{-\lambda t}; t > 0$ 	<ul style="list-style-type: none"> • λ: inverse of the mean 	<ul style="list-style-type: none"> • $\hat{\lambda}^{-1} = \frac{1}{n} \sum_{i=1}^n t_i$
• Gamm a	$\frac{t^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)} e^{-t/\beta};$ <ul style="list-style-type: none"> • $\alpha > 0, \beta > 0, x > 0$ 	<ul style="list-style-type: none"> • α: shape param. • β: scale param. 	$\hat{\alpha}\hat{\beta} = \bar{x}_n$ <ul style="list-style-type: none"> • $\frac{1}{n} \sum_{i=1}^n \ln x_i = \ln \hat{\beta} + \psi(\hat{\alpha})$ *
• Weibu ll	<ul style="list-style-type: none"> • $\frac{cx^{c-1}}{\alpha^c} \exp(x/\alpha)^c$ 	<ul style="list-style-type: none"> • α: scale param. • c: shape param. 	$\hat{\alpha} = \left(1/n \sum_{i=1}^n x_i^{\hat{c}}\right)^{1/\hat{c}}$ <ul style="list-style-type: none"> • $\hat{c}^{-1} = \left(\sum_{i=1}^n x_i^{\hat{c}} \ln x_i\right) \left(\sum_{i=1}^n x_i^{\hat{c}}\right)^{-1} - \frac{1}{n} \sum_{i=1}^n$ †
• Binom ial	<ul style="list-style-type: none"> • $\binom{n}{i} p^i (1-p)^{n-i}$ 	<ul style="list-style-type: none"> • p: prob. of event 	<ul style="list-style-type: none"> • $\hat{p} = r/n$ • r=number of times event happens out of n trials
• Poisso n	<ul style="list-style-type: none"> • $\frac{\lambda^k}{k!} e^{-\lambda}$ 	<ul style="list-style-type: none"> • λ: Mean n. of events per unit of time, length, surface, 	<ul style="list-style-type: none"> • $\hat{\lambda} = r/n$ • r= number of events • n= sample size (time, length,

		etc.	surface, etc.)
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*The solutions of this system of equations, where ψ stands for the digamma function, are the maximum likelihood estimators. [†]c is estimated recursively from the second equation, later on its estimate is substituted in the first one in order to get the estimator of α .

The Bayesian update of information

From all what has been discussed so far, we may deduce that two interpretations of probability may be used in risk analysis and performance assessment: the subjectivist (Bayesian) interpretation for one-of-a-type events and propositions and the frequentist for repetitive events. Though effectively, both cases could be included in the first one (Bayesian interpretation) for, if information about relative frequencies is available, the requirement of coherence will force subjectivists to assign probabilities very close to the observed relative frequencies.

The Bayesian interpretation of probability makes Bayes' formula a powerful tool to update degrees of belief when new information is available about an event or a proposition. Let H be the knowledge of a person (expert), and let $\{z_i\}_{i \in I}$ be a partition of the sample space of events. The Bayesian probability attributed by an expert to a given event z_k is $P(z_k|H)$. The acquisition of a set of new evidence H' produces a change in the probability given by Bayes' formula

$$P(z_k|H, H') = \frac{P(H'|H, z_k) \cdot P(z_k|H)}{P(H'|H)}, \quad (6.7)$$

where $P(z_k|H, H')$ is the 'a posteriori' probability of z_k , $P(z_k|H)$ is the 'a priori' probability of z_k and $P(H'|H, z_k)$ is the likelihood of evidence conditional on the knowledge H and the occurrence of event z_k . $P(H'|H)$ is the probability of new evidence conditional on previous knowledge, which may be considered a normalising factor, since the sum of expressions like (6.7) over the whole partition must be 1 (equivalently, the sum of the a posteriori probabilities of all the partition elements must be 1). That probability is given by

$$P(H'|H) = \sum_i P(H'|H, z_i) \cdot P(z_i|H), \quad (6.8)$$

and may be ignored in any intermediate computation. So, equation (6.7) may be written as

$$P(z_k | H, H') \propto P(H' | H, z_k) \cdot P(z_k | H), \quad (6.9)$$

which means that the a posteriori probability is proportional to the a priori probability and to the likelihood of evidence.

Two remarkable results are obtained from (6.7 – 6.9). If the a priori probability of an event is zero, the a posteriori probability will remain zero, even though the evidence against it could be very strong. So, much care should be taken when providing a priori probabilities. Null a priori probabilities should be avoided, unless total evidence about the impossibility of the events or propositions under study is available. In English literature this is called Cromwell's statement⁴³. The second result is related to the existence of strong evidence. In that case, likelihood will be completely dominant and the a priori probability will be almost irrelevant (a posteriori probability and likelihood will be almost equal). This is the case of large sample sizes, for which relative frequencies and Bayesian probabilities will be almost equal.

Suppose we suspect a coin is not balanced (probabilities of getting head and tail are different), then we toss it n times. Before starting the experiments we have no reliable information about the probability p of getting a head, so we choose a non-informative *prior* distribution $\pi_0(p)$, for example a uniform distribution between 0 and 1. The prior distribution describes our state of knowledge about the probability that we want to study. The chosen distribution means that we know nothing at all about p , that is why we consider any possible value as likely as any other one (uniform distribution) and all the values that a probability may take (from 0 to 1). Suppose that the result of the experiment is r heads and $n-r$ tails. This empirical evidence is used in Bayes formula to update $\pi_0(p)$ in order to obtain a new (posterior) distribution for p

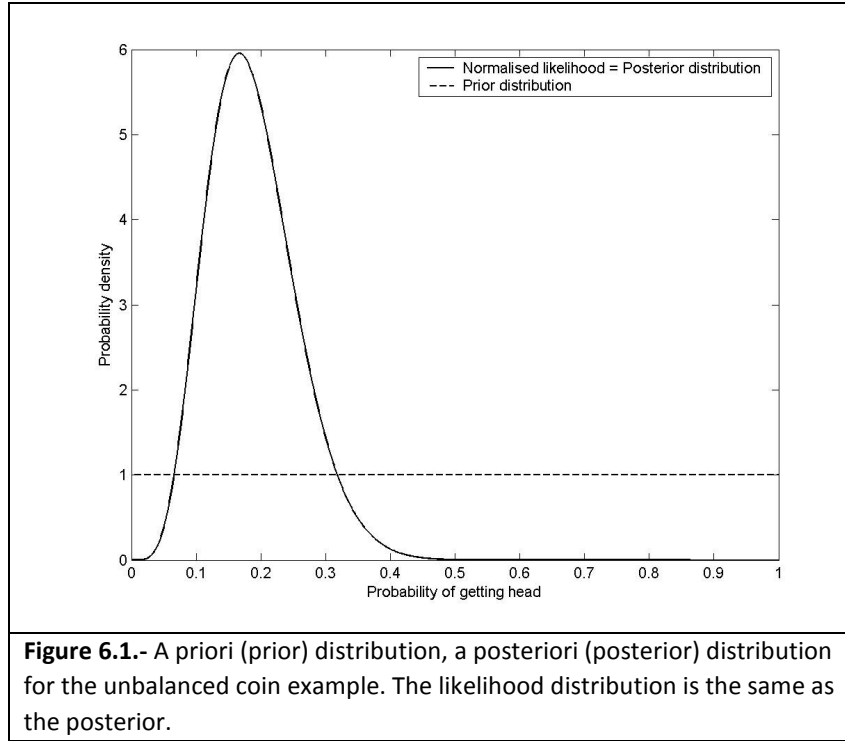
$$\pi_1(p) \propto p^r (1-p)^{n-r} \cdot \pi_0(p) \quad (6.10)$$

where the likelihood associated to the empirical evidence is obtained from the well-known formula for a Bernouilli process. When n is large (strong evidence), the likelihood is almost null everywhere except in a small interval around $p=r/n$, where it reaches its peak. As an example, if $n=30$ and $r=5$, we obtain the following (posterior) distribution for p

$$\pi_1(p) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha) \cdot \Gamma(\beta)} p^{\alpha-1} (1-p)^{\beta-1} = \frac{\Gamma(32)}{\Gamma(6) \cdot \Gamma(26)} p^5 (1-p)^{25} \quad (6.11)$$

⁴³ Gentlemen, I beseech ye, think ye, in the bowels of Christ, that ye may be wrong. Sir Oliver Cromwell addressing Parliament around 1651.

Figure 6.1 shows $\pi_0(p)$ and $\pi_1(p)$ for this example. When the prior distribution is non-informative, the posterior distribution is exclusively determined by the data (likelihood and posterior distributions are equal). The posterior distribution is significantly different from 0 around $p=5/30 \approx 0.17$. So, a coherent person, whose knowledge includes the observation of frequencies obtained from many experiments, will assign subjective probabilities close to the observed frequencies.



Bayesian inferential methods are most used under conditions of scarcity of data. The main steps of the formal process are similar to the steps of a classical inferential process: The selection of the probability model, the estimation of parameters and the diagnosis of the model. The main difference is in the estimation process, which is subject to the use of Bayes formula, as explained above. In the next paragraphs is an example of Bayesian estimation.

Let us assume a random variable X whose pdf is $f(X|\theta)$. This pdf is completely defined by the parameter θ , that is unknown and we want to estimate it. In order to start this estimation process, under the Bayesian framework, the parameter θ is considered as a random variable characterised through an a priori distribution $\pi(\theta|H)$. The a priori distribution provides information about the values the person/expert expects θ could likely take. In order to improve our knowledge about θ , we take a sample - evidence - $\mathbf{X}=(X_1, X_2, \dots, X_n)$, which will have $P(\mathbf{X}|\theta, H) = \prod_{i=1}^n f(X_i|\theta)$ as a likelihood function. Applying Bayes' formula provides the a posteriori distribution to be assigned to θ :

$$\pi(\theta|\mathbf{X}, H) \propto P(\mathbf{X}|\theta, H) \cdot \pi(\theta|H), \quad (6.12)$$

which is a new pdf.

Let us assume the specific case of a Gaussian random variable X . Let us also assume that we do not know its mean, μ , though we know its variance, σ^2 . Let us assume that, given our knowledge about it, we think that μ should have some value close to μ_0 , let us also assume that μ could be, equally likely, larger or smaller than μ_0 , and the further away from it the less likely. Under these conditions, a Gaussian a priori pdf for μ , with mean μ_0 and variance σ_0^2 , could be justified. So that $\pi(\mu|H) \sim N(\mu_0, \sigma_0^2)$. Given a sample taken from the studied variable, its associated likelihood would be:

$$P(\mathbf{X}|\mu, H) = (2\pi\sigma^2)^{-n/2} \cdot e^{-\frac{1}{2}\sum_{i=1}^n \left(\frac{X_i - \mu}{\sigma}\right)^2}. \quad (6.13)$$

When putting this expression into (6.13) and after some computations, we obtain as an a posteriori distribution for μ

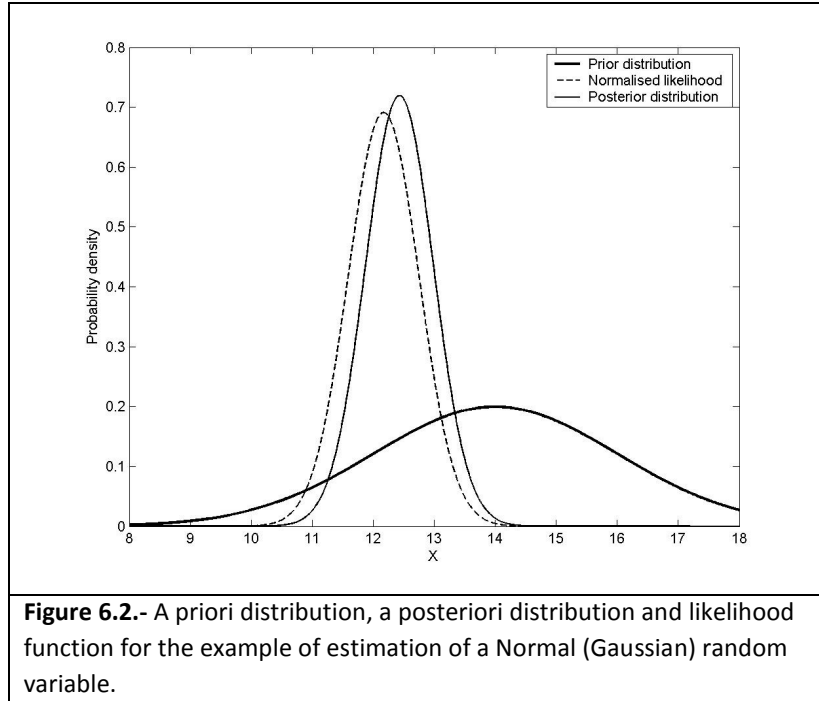
$$\pi(\mu|\mathbf{X}, H) \sim N(\mu_n, \sigma_n^2), \quad (6.14)$$

where μ_n and σ_n^2 are

$$\mu_n = \frac{\frac{n\overline{X_n} + \mu_0}{\sigma^2 + \frac{1}{\sigma_0^2}}}{\frac{n}{\sigma^2} + \frac{1}{\sigma_0^2}} \quad \text{and} \quad \sigma_n^{-2} = n\sigma^{-2} + \sigma_0^{-2}. \quad (6.15)$$

A priori, μ was considered to take values around μ_0 , while after getting the information contained in the sample, values considered likely are those around μ_n . Additionally, the larger the sample size n , the closer μ_n and the sample mean, $\overline{X_n}$, will be (the larger n the larger the information contained in the sample is, while the a priori information remains constant). σ_n^{-2} is the accuracy of the estimation (the sum of the accuracy of the a priori distribution, $1/\sigma_0^2$, and the sample accuracy, n/σ^2). The larger the a priori knowledge and the larger the sample size are, the larger the accuracy (the smaller the variance) of the a posteriori knowledge about μ . Figure 6.2 shows the normalised likelihood, and the a priori and the a posteriori pdfs assuming the following data: $\sigma^2 = 2$, $\mu_0 = 14$, $\sigma_0 = 2$ and $\mathbf{X} = (-3, 15, 23, 8, 13, 17)$. As previously described, the mean of the a posteriori distribution, $\mu_n = 12.43$, is between the mean of the a priori distribution, $\mu_0 = 14$, and

the point where the likelihood function reaches its maximum, $\overline{X}_n = 12.17$. With the classical Maximum Likelihood Method, the estimate would be: $\hat{\mu} = \overline{X}_n = 12.17$.



The validity of this estimation method is supported by:

- 1) its consistency with the way human beings learn from experience, and
- 2) by its convergence to the results provided by the Maximum Likelihood Method when the sample size increases (after analysing the first expression in (6.15), the reader may check that when sample size increases, the mean of the a posteriori distribution converges to the sample mean, which is the estimator of μ provided by the Maximum Likelihood Method), independent of the election of the a priori pdf, except in the aforementioned case of null a priori probabilities.

Much more information on classical and Bayesian estimation is available in the statistical literature, *inter alia*

Casella, G. and Berger, R.L. (1990). Statistical inference. Duxbury Press.

Box, G.E.P. and Tiao, G.C. (1973). Bayesian inference in statistical analysis. Wiley Classics Library. Wiley.

ANNEX 7

Expert Judgement protocols and techniques

Expert Judgement (EJ) has been used during roughly the last seventy years in different areas of science, technology, weather forecasting, strategic planning, economy and many other fields as a reasonable way to assess uncertainties about events and variables when the source of uncertainty is lack of knowledge (epistemic uncertainty). Several structured protocols and techniques have been proposed and improved thanks to the experience acquired in many applications.

In the following pages a short description is given of the most used EJ techniques to assign probabilities to events and probability distributions to uncertain parameters; a well known structured EJ protocol is also described. At the end of this annex is a list of references.

Techniques to assess probabilities and probability distributions

EJ techniques may be used to estimate probabilities of events and probability distributions of continuous and discrete parameters. The next two sections are dedicated to these techniques.

TECHNIQUES TO ESTIMATE PROBABILITIES OF EVENTS

Subjects are not very used to making statements in terms of probabilities, with the exception of persons with some expertise in probability and statistics, and gamblers. Some precision is expected from experts, and preferably they are expected to distinguish between low probabilities such as 10^{-3} and 10^{-4} . In some cases, even if they are able to distinguish between similar likelihoods, perhaps they are not able to express them in the typical scale between 0 and 1. That is why some techniques have been developed to make easier that translation from qualitative opinions to quantitative statements. The techniques may be classified as direct and indirect. Direct techniques may change the scale used to assess probabilities in order to adapt it to the capability of the expert. Indirect techniques use the preferences of experts between different alternatives to derive probabilities and are very useful in helping subjects that are not familiar with the concept of probability.

Direct techniques

The most straightforward technique of assessing a probability is to estimate it directly, but this is not always found as the most suitable way by some subjects; other alternative scales may be used. Two of these scales are the odds and the log-odds, which are

$$odd = \frac{P}{1-P} \quad (7.1)$$

$$\log\text{-odd} = \text{Log}\left(\frac{P}{1-P}\right) \quad (7.2)$$

The odd is the quotient between the probability of the event and the probability of the complement of that event. The log-odd is the decimal logarithm of the odd. Figures 7.1 and 7.2 show the scales used when those magnitudes are used to make probabilistic statements (the range of the odd scale is $[0, +\infty)$ while the range of the log-odd scale is $(-\infty, +\infty)$).

Some subjects are more capable of making probabilistic statements when they use the jargon of gamblers; they express their uncertainty about events via expressions such as 'h against k in favour of the occurrence of the event'. When this jargon is used, the two following identities proceed

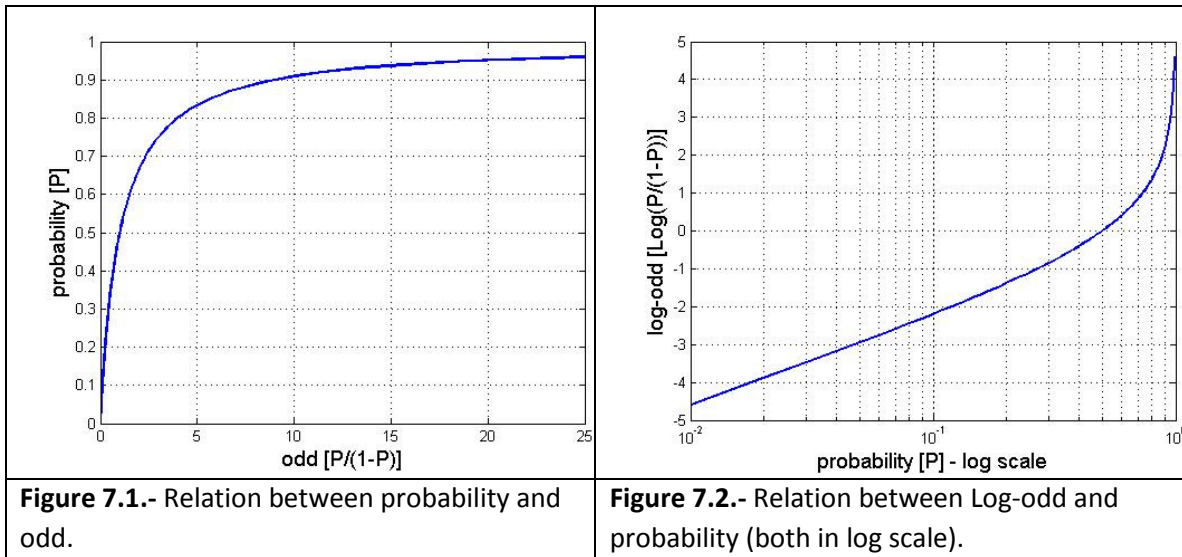
$$P = \frac{h}{h+k} \quad (7.3)$$

and

$$\text{odd} = \frac{h}{k} \quad (7.4)$$

where P is the probability of the event. When using this scale, a probability 10^{-3} would be formulated as 'roughly 1 against 1000 in favour of the occurrence of the event' (strictly speaking 1 against 999).

The use of odds and log-odds involves stretching the scale where probabilities are assessed, which should lead to an improved resolution. When the usual (linear) probability scale is used, it is not so easy to distinguish between probabilities such as 0.48 and 0.50, giving preference to 'nicer' numbers, 0.50 in this case.



Indirect techniques

Savage (1954) believes that direct methods introduce large errors (discrepancies between assessed probabilities and honest beliefs) because subjects are not good probability assessors; this is the reason why he proposes using methods that do not mention probabilities explicitly. Savage proposes a technique called 'certainty equivalence'. This technique consists in proposing to the expert a game: he/she will get an economic reward if the event he/she is asked the probability of occurs; otherwise he/she gets no reward. Then he/she is asked up to what quantity of money he/she would be willing to pay in order to participate in the game. The probability of the event is then assessed as the quotient between the maximum quantity of money he/she would be willing to pay to be allowed to participate in the game and the economic reward. An equivalent alternative is to propose the expert to choose between the next two options: getting y Euros if the event happens and getting nothing if it does not happen or getting a quantity x (not higher than y) independently of the occurrence or not of the event. The quantity x is increased until the point when the subject has no clear preference between both choices. The probability assessed would be the solution of the equation $x = P \cdot y + (1 - P) \cdot 0$, which is $P = x / y$.

De Finetti (1974) does not trust this type of technique for assessing probabilities because, in his opinion, probabilities become biased by the attitude of the subject towards gambling. As an alternative he proposes a technique called the 'reference lottery'. The subject is confronted with two lotteries. In the first one he/she gets a reward x with probability P and a smaller reward y with probability $1-P$, while in the second one he gets the reward x if the event A happens and y if it does not happen (see figure 7.3). The subject has to choose one of them. P is varied until when the subject has no clear preference between both choices, the value of P at that moment is the probability assessed by him/her for the event. The fact that the reward is the same in both lotteries is designed to remove biases produced by different attitudes towards gambling.

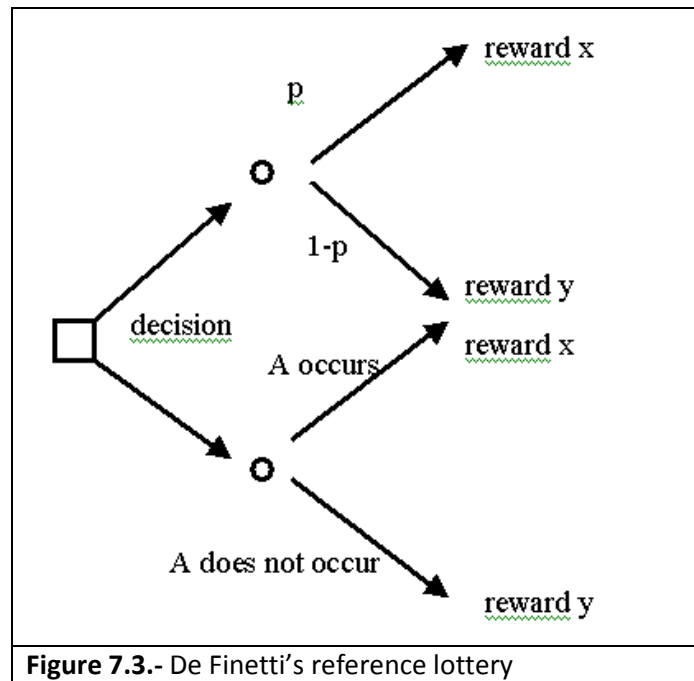


Figure 7.3.- De Finetti's reference lottery

Raiffa (1968), due to the same reasons that brought De Finetti to propose the reference lottery, proposed the 'reference urn' method. The subject is encouraged to imagine an urn that contains balls with two different colours. The subject will be asked what ratio between the balls of both colours best corresponds with his opinion about the occurrence of a given event. Although this technique and the reference lottery seem appropriate to be used with subjects that do not have a good background in probability, many analysts find them tedious and difficult to apply in real expert judgement applications; they consider them useful only if either they are used to assess only a few probabilities or to introduce probabilistic concepts in the first steps of a protocol.

TECHNIQUES TO ASSESS PROBABILITY DISTRIBUTIONS FOR UNCERTAIN PARAMETERS

The techniques to help experts in assessing probability distributions may be divided into techniques targeting continuous distributions and techniques targeting discrete distributions. The techniques used to assess continuous distributions are based on the assessment of probabilities of discrete events such as 'the parameter value lies between this and that values'.

Discrete distributions

In the general case, experts need to assess the probabilities of n different possible values of the parameter under study. These n values may be considered as n different mutually exclusive events. When n is too large, say 10 or larger, it is convenient to group them in a smaller set. The first step is to ask the expert to rank them from the most to the least probable and to provide a rationale to justify such ranking. Later on, the individual probabilities are assessed. Usually the expert is asked firstly about the probability or the odd of the most likely value. In case the expert does not feel comfortable giving his/her assessment in terms of either probabilities or odds, other alternative techniques may be used.

The fact that the probability of all possible values has to add up to 1 makes it unavoidable to estimate the probabilities of at least $n-1$ values, the n^{th} may be deduced from the normalisation condition, yet it is advisable to understand the whole rationale of the expert, asking him the n probabilities, checking the normalisation condition later on. If the estimated probabilities do not add 1, it is always interesting to find out the reasons for such inconsistency. Normalisation may always be easily achieved, the normalisation constant k being obtained by solving the equation $k (\sum_{i=1}^{i=n} p_i) = 1$. More sophisticated normalization techniques have been proposed by Lindley et al. (1979).

Continuous distributions

Two techniques are available to assess continuous distributions for uncertain continuous parameters: the quantile technique and the interval technique. The first of them is based on fixing probabilities and asking experts about the corresponding values of the parameter, while the second one consists in fixing values and asking about probabilities. Sometimes both techniques are combined in the same elicitation session. Other more complicated techniques, which require higher than average statistical skills can also be used, but some authors believe that these are not always well understood by subjects.

- **The quantile technique**

Given a random variable X with distribution function $F(x)$, its quantile q is the value x_q such that X takes values equal to or smaller than it with probability q , i.e.: $F(x_q)=q$. x_q may also be called percentile $100 \cdot q$ %. The quantile 0 is the lower bound of the parameter under study and the quantile 1 is the upper bound. Quantile 0.5 is the median. The cumulative distribution function of X consists in plotting q versus x_q .

The application of these techniques begins by asking the expert about the upper and lower bounds of the parameter. If the expert is not able to provide such absolute bounds, then analysts ask about quantiles 0.99 and 0.01, or 0.95 and 0.05, depending on how comfortable the expert feels in estimating extreme values. It is important to combine these direct questions with others oriented to counteract overconfidence. These kinds of questions should encourage the expert to think of conditions under which the parameter could take values outside the boundaries previously assessed and the likelihood of such conditions. It can be very beneficial for the analysts to help the expert in imagining such situations either by 'digging' into the problem or providing examples that came up in similar expert judgement applications. Einhorn and Hogarth (1978) note that experts frequently make good use of this type of help. In general, thinking of alternative conditions help experts in broadening their uncertainty ranges.

Once the upper and lower bounds, or some given extreme quantiles have been assessed, then the analyst asks about the median. The expert is asked about a value that could be equally likely smaller or larger than the actual value of the parameter. It is important to see how far this estimate is from the previously estimated bounds or extreme quantiles. If the estimate is more or less in the middle, this could mean that the expert is just taking the mean of the extreme values or considering some kind of implicit symmetry. Medians too close to some of the bounds could also indicate a poor original definition of the bounds. The expert should be asked about the reasons for providing that estimate for the median. Later on, quantiles 0.25 and 0.75 are addressed using similar questions. More quantiles may be assessed, but five quantiles are usually enough to draw an approximate cumulative distribution. The shape of the curve should be discussed with the expert in order to uncover potential inconsistencies. It is also useful to draw the pdf and show it to the expert, since features like the symmetry or lack of symmetry of the distribution are easier to see in the pdf than in the cumulative distribution.

It is important to address extreme quantiles and absolute bounds as the first steps of the elicitation session. In the first applications of this technique the bisection method became very popular. It consists of asking firstly for the median, asking then for the 25% and the 75% and so on. Nowadays this method has been abandoned because it was experimentally shown that asking firstly for the median converts this estimate into an anchor that quite frequently led to overconfidence.

- **The interval technique**

In order to apply this technique, the analyst selects some values and asks the expert about the probability that the parameter is located within the different intervals defined using those values. There are two types of intervals to define: open intervals and closed intervals. In the first case the analyst selects a point and asks the expert the probability of the value of the parameter being smaller (or larger) than it. In the second case the analyst selects two points and asks the expert the probability that the value of the parameter be inside the defined interval. If the expert finds difficulties in giving his/her opinions in terms of probabilities, the analysts can help him/her using indirect techniques.

In both cases (open and closed intervals), in order to avoid overconfidence due to introducing an anchor given by a first estimate about a central value, the analyst starts by posing questions related to very extreme values, that should correspond to quantiles such as 0.01, 0.05, 0.95 and 0.99, or even to absolute bounds. Later on, some other interior points are selected, usually between three and seven, depending on the degree of accuracy required, and the analyst asks the expert questions based on them. Each answer given by the expert must be supported by some rationale, and the expert should be confronted with conflicting data and with hypothetical situations not considered or mentioned in his/her rationale. When the closed interval option has been selected, another convenient task to do is to ask the expert to rank from the most likely to the least likely a number of intervals whose limits are set using the group of values selected. With the information obtained from the expert the cumulative distribution functions and the corresponding pdfs are built and results are discussed to check consistency.

An Expert Judgement protocol: the Stanford Research Institute (SRI) protocol

This is the first structured protocol developed to obtain individual expert judgements and can be considered as the precursor of most of the others. It was developed in the 1960's and 1970's by the Decision Analysis Group of the SRI (Stanford University). The protocol was originally divided in five phases, though it was further enlarged, see Merkhofer (1988), after the dissolution of the Decision Analysis Group. In this protocol, the process to obtain the opinion of the experts is considered as the joint task of an analyst and an expert. A description of the protocol follows:

- **Phase 1: Motivating**

The objective of this phase is a first contact with the expert in order to inform him/her about what is expected from him/her and to find out if there is any risk of encountering motivational biases.

Firstly, the analyst explains to the expert the general problem to be solved and the context in which his/her opinions are meaningful. The expert is informed about the importance of the parameter or event under study, he/she is also informed about the way the opinions provided will be used within the general problem. Then the expert is informed about the fact that the objective is not to forecast a single value but to characterise the uncertainty about the parameter of interest.

- **Phase 2: Structuring**

The purpose of this phase is twofold. On the one hand, the objective is to decompose the quantity of interest as a function of several other variables in order to simplify the task of assessing distribution functions, on the other hand the objective is to obtain information about the way the expert approaches the problem, identifying implicit hypotheses that were unknown to the analyst and that could introduce bias into the assessment results. This phase may be divided into three steps:

1. To set an accurate definition for the parameter under study: The parameter under study must be precisely defined.
2. Study the possibility of decomposing the quantity of interest: Decomposing the quantity of interest may help in counteracting the effects of motivational biases. Working on low-level variables may help in disconnecting an expert's assessments from his/her personal interests, which are based on high-level variables, or attitudes towards risk and uncertainty.
3. Explicitly set all hypotheses to be used by the expert: The objective is to uncover all implicit and explicit hypotheses considered by the expert in his/her assessment. A useful method of uncovering implicit hidden hypothesis is to ask him/her what he/she would like to insure against. In other words, if he/she were allowed to take insurance on certain events that could make his/her estimates wrong, what would be those events? Finally, the units to be used in the assessment for the quantity of interest or for any low-level variable that comes up in the decomposition process must be clearly stated. Experts should be allowed to choose the units they prefer to use.

- **Phase 3: Conditioning**

The purpose of this phase is to draw out into expert's immediate consciousness all relevant knowledge related to the uncertain quantity. Usually, when dealing with a problem, we have generic (or distributional or base information) and case-specific information. It is important to realise both types of information and combine them adequately. Usually subjects ignore generic information and base their opinions on case-specific information. In order to avoid this situation, the authors propose to ask experts the following question: In your opinion, what would be the answer to this question given by another person with no case-specific information? The answer provided by experts could be taken as a prior distribution that could be combined with the opinion based on only case specific information to get the posterior distribution through the use of Bayes' formula. In this phase experts are also warned about the risk of using data with no predictive capability to make predictions. They propose to use a method suggested by Tversky and Kahneman (1982) to correct such kind of problems, which in fact implies a regression to the mean. These authors propose the following *measure of predictability* $\tau = 2 \cdot \rho - 1$, where ρ is the correlation coefficient (in general a subjective estimate) between predictions and outcomes. Then, if the expert provides an estimate Y , when the mean of the prediction is μ_Y the estimate should be corrected towards the value $\mu_Y + \tau \cdot (Y - \mu_Y)$. It must be pointed out that this correction can be used only for absolute values of ρ above 0.5. In any

other case (weak correlations described by correlations coefficients between -0.5 and 0.5) the suggestion of the authors is to use the mean (extreme case of regression to the mean).

In this phase experts are encouraged to think of scenarios that could produce either extremely high or extremely low values of the quantity and think about their likelihood. If needed, experts could be invited to do a calibration exercise.

- **Phase 4: Encoding**

This is the phase where the analyst and the expert together build the distribution function. The techniques used in this protocol are the quantile and the interval techniques, and the combination of both. Experts are allowed to choose the scale they prefer to make their probabilistic statement (probabilities, odds, log-odds, bets, etc.). Indirect techniques such are also accepted.

Consistency of expert's assessments must be checked from time to time by asking the same or similar questions in different ways. Lack of consistency may be also detected by drawing the estimates provided by the expert on graph paper. In some cases, the first points lie on one line while subsequent points lie on a shifted different one. Usually this means that after a given point in the encoding session the expert started taking into account in the assessment some additional information. Under these circumstances it could be convenient to repeat the encoding session.

- **Phase 5: Verification**

The objective of this phase is to check that the expert agrees with the distribution generated during the encoding phase. The pdf and the cumulative distribution are plotted. Reviewing those plots could highlight some effect not foreseen by the expert that could warrant some further discussion. The final step is to ask the expert if he/she would be willing to bet on his/her estimates. If the expert does not feel comfortable with the distributions generated, some phases of the protocol should be repeated, at least the encoding phase.

- **Phase 6: Aggregation**

This phase was added after the dissolution of the Decision Analysis Group. The original protocol was designed to elicit judgements from only one expert. In many cases it is necessary to gather the judgment from several experts. In that case aggregation would be necessary. The aggregation should be done by mathematical means, preferably using a linear pool, see Bolado et al. (2009), either with equal or with unequal weights.

More information about EJ structured protocols and techniques may be found in Bolado et al. (2009).

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ANNEX 8

Relevant issues for gas market modelling A categorization

The energy system is a formidably complex and crucially important element of the overall economic-social-technical system. It can be described in a number of different ways, and through the languages and characterizations of a number of different disciplines, including at least the so called '4Es': energy, engineering, economy, environment.

A 'system' approach attempts to include all the significant elements of the system under study and emphasizes: a) the relations and interactions between them, b) the synergies and the integral nature of the system. The use of *mathematical* models/tools makes possible to assess quantitatively the impact of choices. The use of *formal* models ensures consistency, reproducibility and transparency (relationships are specified in formal terms and all variables are measured in consistent units).

However, there are several different categories of models. The choice among them can be done only after considering the type of policy to be evaluated, or more generally the type of analysis to be developed.

Identification and categorization of the relevant issues for quantitative assessments of energy security

Aim of the framework presented here is to clarify the methodological requirements to address different energy security threats and different insurance strategies, each one characterised by its own specific characteristics. Once the threats have been categorised (see Main Report, 3.2.1) the next step is the identification of the methodological requirements which must be taken into account to assess any threat category. To this end, the relevant issues for modelling the various aspects of energy security are here identified and briefly discussed. The issues which are related have been grouped by using the criteria normally adopted to categorize energy models: three main wide dimensions (plus several sub-dimensions) have been defined. These three dimensions make possible to clearly contrast the two conventional modelling approaches (Top-Down/Bottom-Up), at the same time providing a useful framework for the analysis.

Following Hourcade et al.⁴⁴, the characteristics of conventional TD and BU models can be synthesised by placing them inside a three-dimensional graph: "to be particularly useful, an energy-environment policy model should *technologically explicit*, *behaviorally realistic* and have *macroeconomic feedbacks*. This categorization of energy-economy models is useful to identify the main "model families", but it still falls short of being a framework to identify the methodological requirements for energy security assessments. To this end, in the following the three main dimensions adopted above have been exploded and partially renamed. The renaming just gives a more general significance to macro-economic completeness and

⁴⁴ Hourcade et al., 2006, Hybrid Modeling: New Answers to Old Challenges, The Energy Journal, Special Issue on Hybrid modeling of energy-environment policies: reconciling bottom-up and top-down.

technological explicitness, by using the wider concepts of system boundary and granularity. Each of these dimensions has then been exploded, in order to cover all the issues which are relevant for assessing energy security, not only in a modelling framework but in any quantitative and rigorous framework. Aim of this “modelling perspective” is to help identify the elements of the system that must be considered in any specific assessment, making evident what are the characteristics of the “ideal” tool to be selected and used.

Table 8.1 – Framework for a classification of energy-economy models

Main dimension	Sub-dimension	Possible options
Scope/System boundary	Sector	Economy/Macro, Energy System, Energy sector
	Market	Multi-energy markets, Single-energy market
	Geographical scope	Global/Multi-country, EU/Multi-country, Regional, Country
	Dynamics / Time horizon	Short-term, Medium-term, Long-term / Static, Dynamic
Granularity	Technology representation	black box, detailed
	Supply Chain	Upstream, Storage, Supply, End-uses
	Environmental detail	Emissions, Water, Biodiversity
	Infrastructures and network	Network type, Transportation type, None
	Energy transition technology	AEEI (Exogenous), Endogenous, None
	Time step	Hours, Intra-day, Day, Week, Season, Year
Realism	Market description / imperfections	Perfect competition, Strategic behaviour
	Agents behaviour	Perfect rationality, Bounded rationality, Not considered
	Price formation	Endogenous, Exogenous, Not considered
	Out-of-equilibrium dynamics	yes, no

Existing quantitative tools/models; a categorization

After having identified and categorized the issues which are relevant for the gas market analysis/modelling (Table 8.1), Table 8.2 uses the same framework to classify some existing quantitative tools/models used to analyze energy/gas security issues. This survey does not aim to be comprehensive. Its aim is instead to show how the wide range of models available in the main literature can be differentiated on the basis of the theoretical framework proposed above.

As the choice of the issues to be simulated are strictly country/region dependent, any Member State can either carry out its assessment by developing a model with the desired characteristics or consider the possibility to use one of the existing models.

Table 8.2 - Clarifications/definition of the aim(s) of the regulation (and of its possible measures)

		Model Name	Institution	Sector	Market	Geographical scope	Dynamics / Time horizon	Technology representation	Supply Chain	Environmental detail	Infrastructure and network	Energy technology transition	Time step	Market description / imperfections	Agents behaviour	Price formation	Out-of-equilibrium dynamics
Macroeconomic models	Macro-economic	E3MG/E3ME	Cambridge Economics Un.Cambridge	Economy /Macro	Multi-energy markets	Global/Multi-country	Long-term/Dynamic	black box	Upstream, Transform., Final Demand	emissions	-	AEEI (Exogenous)	year	imperfect competition	Bounded rationality?	Endogenous	yes
	CGE	GEM-E3	CES-KULeuven	Economy /Macro	Multi-energy markets	Global/Multi-country	Long-term/Static	black box	Upstream, Transform., Final Demand	emissions	-	AEEI (Exogenous)	year	perfect competition	Perfect rationality	Endogenous	
		GTAP-E	Purdue Univ., USA	Economy /Macro	Multi-energy markets	Global/Multi-country	Long-term/Static	black box	Upstream, Transform., Final Demand	emissions	-	AEEI (Exogenous)	year	perfect competition	Perfect rationality	Endogenous	
Energy system models		POLES	IEPE, France	energy sector	multi-energy markets	Global/Multi-country	Long-term / Dynamic	black box	Upstream, Transform., Storage, Supply, Final Demand	emissions	transp.	Endogenous	Intra-day / Seasons	perfect competition	perfect rationality	Endogenous	no
		PRIMES	Univ. of Athens, Greece	energy sector	multi-energy markets	EU/Multi-country	Long-term / Dynamic	black box + detail	Upstream, Transform., Storage, Supply, Final Demand	emissions	transp.	Endogenous	Intra-day / Seasons	perfect competition	perfect rationality	Endogenous	no
		ETP	IEA	energy sector	multi-energy markets	Global/Multi-country	Long-term / Dynamic	tech-by-tech	Upstream, Transform., Storage, Supply, Final Demand	emissions	transp.	Endogenous	Intra-day / Seasons	perfect competition	perfect rationality	Endogenous	no
		TIAM-PET - RECOR	FP7 proj. REACCESS	energy sector	multi-energy markets	Global/Multi-country	Long-term / Dynamic	tech-by-tech	Upstream, Transform., Storage, Supply,	emissions	network/transportation (?)	Endogenous	Intra-day / Seasons	perfect competition	perfect rationality	Endogenous	no

			Final Demand														
Energy sector models	NATGAS	CPB - NL	energy sector	gas market	EU/Multi-country	Long-term / Dynamic	black box	Upstream, Storage, Supply, Final Demand	-	transp.	-	year	strategic behaviour (upstream)	perfect rationality	endogenous	no	
	GASTALE	ECN - NL	energy sector	gas market	EU/Multi-country	Long-term / Dynamic	black box	Upstream, Storage, Supply, Final Demand	-	transp.	-	year	strategic behaviour (upstream)	perfect rationality	endogenous	no	
	GASMOD	DIW (DE)	energy sector	gas market	EU/Multi-country	Long-term / Dynamic	black box	Upstream, Storage, Supply, Final Demand	-	transp.	-	year	strategic behaviour (upstream)	perfect rationality	endogenous	No	
	Pegasus	Poyry, UK	energy sector	gas market	EU/Multi-country	Long-term / Dynamic	black box + tech-by-tech (Transp., Storage)	Upstream, Storage, Supply, Final Demand	-	transp. (?)	-	day	perfect competition	perfect rationality	endogenous	No	
	World Gas Trade Model	RICE Univ. (US)	energy sector	gas market	Global/Multi-country	Long-term / Dynamic	black box	Upstream, Storage, Supply	-	transp.	-	year	perfect competition	perfect rationality	endogenous	No	
Infrastructure and network	EUGAS / TIGER	EWI - Univ. Cologne (DE)	energy sector	gas market	EU/Multi-country	Medium-term/statistic (?)	no	Upstream, Storage, Supply	-	network (?)	-	day	perfect competition	perfect rationality	endogenous	No	
	WASP	IAEA															
	CGEN	Cardiff Univ., Wales, UK															
	GEMFLOW	JRC-IE	energy sector	gas market	EU/Multi-country	(very) short-term/stat	no	Storage, Supply	-	transp.	-	day	no	no	not modelled	No	

			ic
Dynamic system			

ANNEX 9

Fault tree and event tree analyses

Fault Tree Analysis (FTA)

Fault trees were first developed for missile launch control reliability back in 1961. It has been an essential part of nuclear safety since 1975 and is widely used in the chemical process industry to address safety and reliability problems during past decade.

Fault tree analysis is a technique for identifying and analysing factors that can contribute to a specified undesired event (called top event). Causal factors are deductively identified, organized in a logical manner and represented in a tree diagram which depicts causal factors and their logical relationship to the top event. To complete the construction of a fault tree for a complicated system, it is necessary to first understand how the system functions. A system flow diagram is used for this purpose. The first step in fault tree construction is then the selection of the system failure event of interest the so called top event. Every following event will be considered in relation to its effect upon it.

Fault tree Analysis permits the top event frequency to be estimated from a logic model of the failure mechanisms of a system. The model is based on the combinations of failures or more basic system components, safety systems, and human reliability.

The underlying technology is the use of a combination of relatively simple logic gates (usually AND and OR gates) to synthesize a failure model of the system. In figure 1, the standard symbols used in Fault Tree Analysis are represented. The top event frequency or probability is calculated from failure data of more simple events. As well as providing quantitative information on top event, the fault tree can provide powerful qualitative insight into the potential failure modes of a complex system through minimal cut set analysis. Minimal cut set analysis is a mathematical technique for manipulating the logic structure of a fault tree to identify all combinations of basic events that results in the occurrence of the top event.

A basic assumption in the FTA is that all failures in a system are binary in nature. That is, a component or operator either performs successfully or fails completely. In addition, the system is assumed to be capable of performing its task if all subcomponents are working. FTA treats only instantaneous failures.

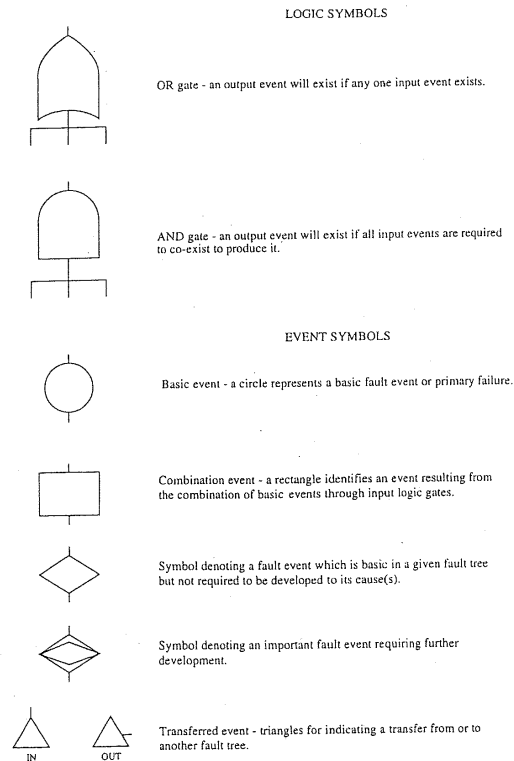


Figure 1: Standard symbols used in Fault Tree Analysis

Example:

An LPG storage tank installation is sited close to a railway line on which trains pass carrying fuel oil to a power station. If a train derailed it may either plough directly into the LPG storage installation or it may overturn with a consequent possibility of the fuel catching fire. The fire may cause the LPG installation to explode.

It is possible to estimate the frequency of explosion of the LPG storage installation using the data below:

Number of fuel oil trains per year	1000
Derailement frequency per km travelled	0.4×10^{-6}
Length of average fuel oil train	0.5 km
Length of LPG installation next to railway line	0.7 km
Probability that a derailed train overturns	0.5
Probability that an overturned train catches fire	0.1
Probability that fire engulfs LPG tanks causing explosion	0.2
Probability that a derailed train hits the LPG installation causing an explosion	0.05

The fault tree for the top event: "LPG explosion" is presented below and provides a frequency of explosion = $2.3 \times 10^{-5} \text{ yr}^{-1}$

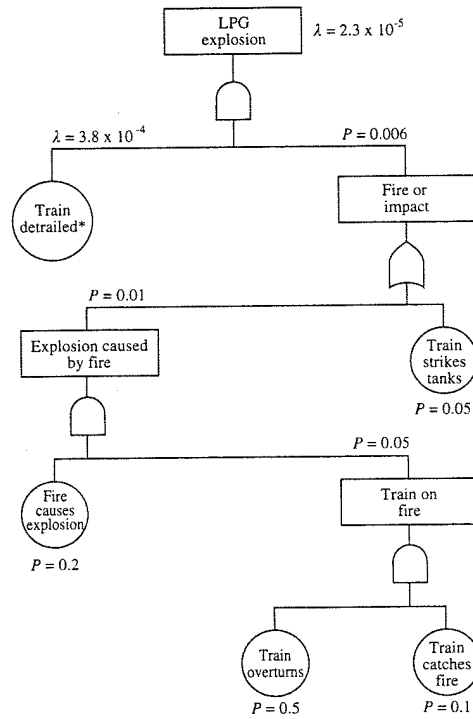


Figure 2: Fault tree representation for the Top Event: LPG explosion

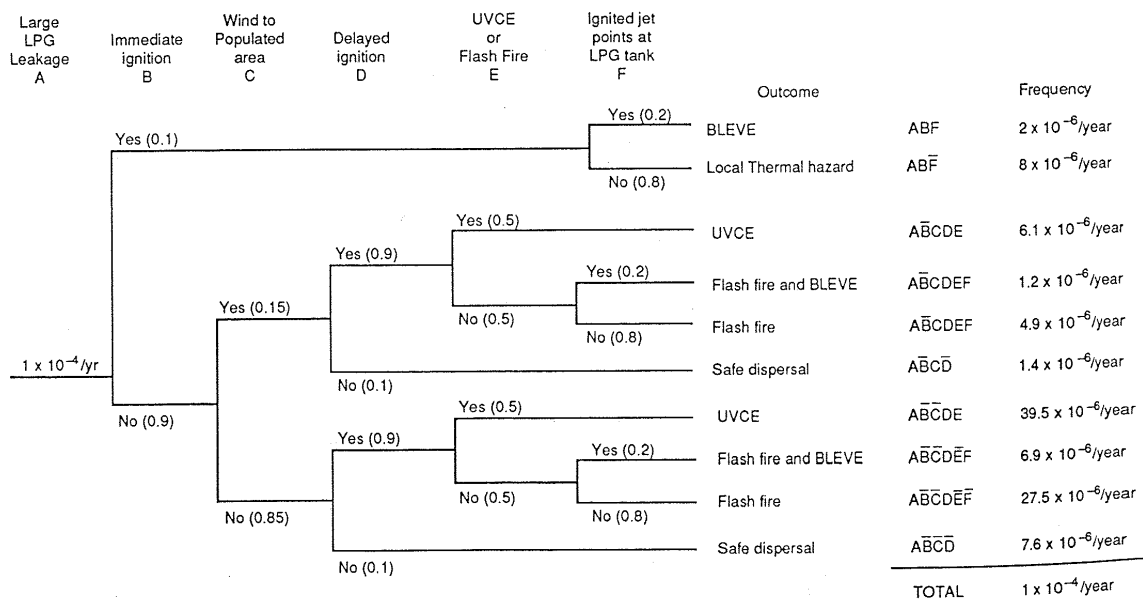
Assuming that the installation is at risk until half the train is passed clear of the last tank, the total vulnerable track length is $0.7 \times 1/2 \times 0.5 = 0.95$. Hence frequency of derailment is $0.95 \times 1000 \times 0.4 \times 10^{-6}$.

Event Tree Analysis (ETA)

Event tree analysis was first developed in the aerospace and defence industry, but has now found widespread applications in risk analyses for both the nuclear and chemical industries.

An event tree is a graphical logic model that identifies and quantifies possible outcomes following an initiating event. It is an inductive approach which works from cause to effect. The event tree provides systematic coverage of the time sequence of event propagation. Event trees are basically a modified form of the logic trees used in decision analysis and describe possible progression from a given initiating event via a series of binary branches representing success or failure of safety features or the occurrence or not of some physical event. Thus the event tree is a diagrammatic representation of all the potential ways in which an event (initiating event) can develop through a system. Two distinct applications can be identified. The pre-incident application examines the systems in place that would prevent incident-precursors from developing into incidents. The event tree analysis of such a system is often sufficient for the purpose of estimating the safety of the system. The post incident application is used to identify incident outcomes. In case of event trees the approach is left to right rather than top to bottom with the initiating event on the left and developing consequences expanding to the right.

Example: post incident analysis of a large leakage of pressurized flammable material from an insulated LPG storage tank. An engineering analysis of the problem indicates that the potential consequences include BLEVE (boiling liquid expanding vapour explosion) of the tank if the leak is ignited. If the leak does not immediately ignite, it can drift toward a populated area with several ignition sources and explode (UVCE: unconfined vapour cloud explosion) or produce a flash fire. In Figure 3 an event tree is presented to predict possible outcomes from the leakages of LPG using some sample event tree data.



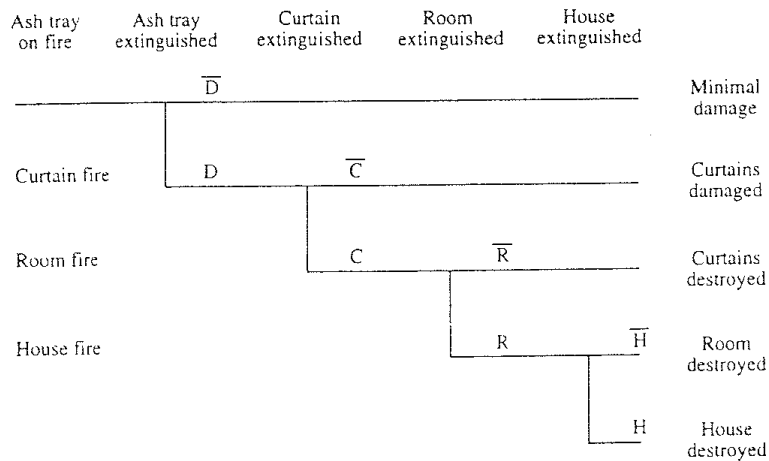


Figure 4: Event tree for cigarette fire

The branch point is where the logic path splits at the nodal question/event- is the ashtray extinguished? Each path or accident sequence is assigned a system outcome that is accident or no accident. The convention used in event trees always put the mitigating or less damaging event in the upper branch. Thus the trees shows and increase in the severity of the consequence as it goes down.

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ANNEX 10

Uncertainty analysis via Monte Carlo

The Monte Carlo method consists in sampling at random the vector of input parameters, running the system model computer code for each sample of that vector and getting a sample of the vector of output variables. Later on, the characteristics of the output variables may be estimated using the output samples obtained. One of the advantages of using the Monte Carlo method is that all statistical standard methods we need to estimate the output variables distributions and to test any hypothesis may be used. This makes it the most straightforward and powerful method available in the scientific literature to deal with uncertainty propagation in complex models. This method is valid for models that have static and also dynamic outputs. It is adequate for working with discrete and continuous inputs and outputs, and the implementation of computational algorithms required has no fundamental complexity.

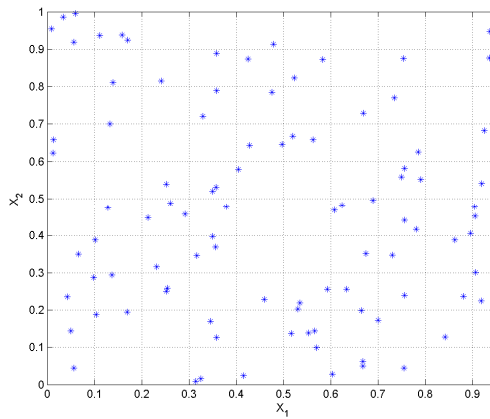


Figure 10.1.- Simple random sample of size 100 of two random variables uniformly distributed in the region $[0,1] \times [0,1]$.

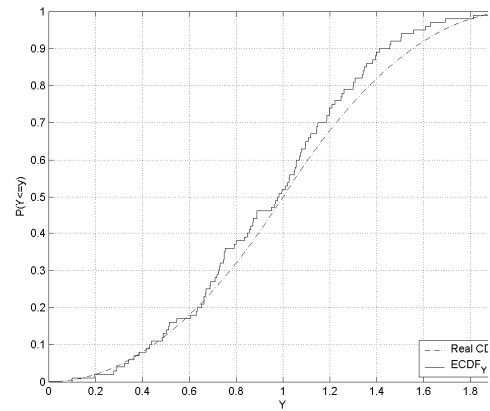


Figure 10.2.- ECDF obtained from a simple random sample of size 100 of $Y = X_1 + X_2$ and its theoretical CDF.

Monte Carlo maps the input space into the output space point by point. In order to see this, let us consider a very simple model: $Y = X_1 + X_2$. Suppose X_1 and X_2 follow independent uniform distributions both of them defined in the interval $[0,1]$. For this simple model an analytical propagation of uncertainties is feasible and the output Y follows a triangular distribution defined in the interval $[0,2]$ and whose mode, mean and median are 1. This propagation may be done via Monte Carlo. First, a sample of size 100 is taken in the input space (see figure

A.1). For each point shown in figure 10.1, the value of the output is then computed. An empirical cumulative distribution function is built from the 100 values obtained (see figure 10.2). For the sake of comparison the actual CDF of Y has also been drawn.

Monte Carlo may also be seen as a numerical integration method. In the same example, let us consider that we are primarily interested in the estimation of the mean of Y . This means that we are trying to estimate

$$\mu_Y = \int_{[0,1] \times [0,1]} (X_1 + X_2) dx_1 dx_2. \quad (10.1)$$

One of the possible approximations to compute this integral is to take the sample considered in figure 10.1 and figure 10.2 and to calculate the arithmetic mean

$$\hat{\mu}_Y = \frac{1}{100} \sum_{i=1}^{i=100} (x_{1i} + x_{2i}). \quad (10.2)$$

It is important to remark that the standard deviation of this estimator is

$$\sigma_{\hat{\mu}_Y} = \sigma_Y / \sqrt{n}, \quad (10.3)$$

where σ_Y is the standard deviation of the output Y .

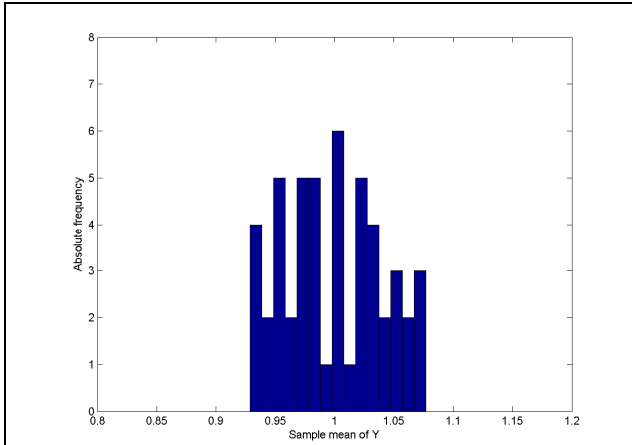


Figure 10.3.- Histogram of the sample means obtained from 50 simple random samples of size 100 obtained via Monte Carlo simulation.

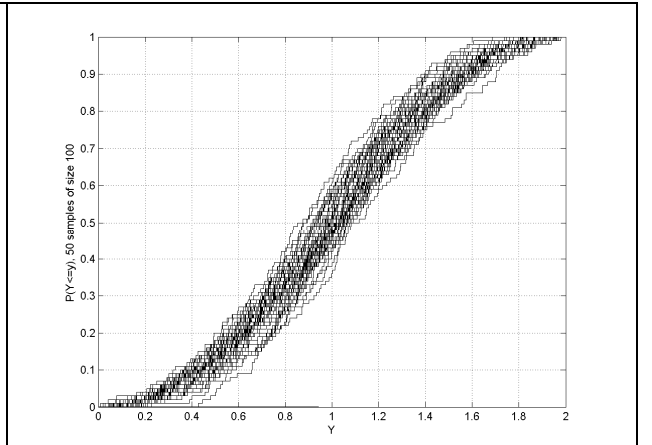


Figure 10.4.- ECDFs obtained from 50 simple random samples of size 100 obtained via Monte Carlo simulation.

Figure 10.3, which shows the histogram obtained from 50 simple random samples of size 100, similar to the one shown on figure 10.1 and figure 10.2. In this plot we can see that the range of $\hat{\mu}_Y$ is roughly 0.2, which means it represents one tenth of the range of Y (the range of this triangular distribution is 2). Figure 10.4 shows the corresponding ECDFs.

It is important to remark that the standard error of $\hat{\mu}_Y$ does not depend on the dimension p of the space where the integral is computed, and that consequently the Monte Carlo

method does not suffer from the curse of dimensionality. Metropolis and Ulam (1949) is the seminal paper about Monte Carlo, where many interesting suggestions are made about its applicability. Readers interested in getting further details about the Monte Carlo method are suggested to see Hammersley and Handscomb (1964), Rubinstein (1981) and Robert and Casella (2004).

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Abstract

The EC Regulation concerning measures to safeguard security of gas supply (EC/994/2010) requires member states to make a full assessment of the risks affecting the security of gas supply. According to Article 9, this risk assessment must:

- (a) use the infrastructure and supply standards (articles 6 and 8);
- (b) take into account all relevant national and regional circumstances;
- (c) run various disruption scenarios;
- (d) identify the interaction and correlation of risks with other Member States.
- (e) take into account the maximal interconnection capacity of each border entry and exit point.

The objective of this report is to provide guidance and advice for performing risk assessments. It will do so by first providing a literature review, and then by proposing a basic structure for undertaking a gas security risk assessment, in accordance with best practices and standard procedures found in risk management

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